PAPER

Performance Analysis of Closed-Loop Like Power Control for Packet Transmission over DS-CDMA in a Multipath Fading Environment

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SUMMARY Packet-based and stream-based traffic will be widely accommodated in third generation mobile systems. In direct sequence code division multiple access (DS-CDMA) systems, the impact of packet-based traffic is different from stream-based traffic because of different power control schemes adopted in a multipath fading environment. In this paper, a closed-loop like power control scheme is considered for packet-based traffic on the reverse link. The concept of packet cost is introduced that represents how packet traffic consumes the link capacity of stream-based traffic. The effects of the response delay, the fading maximum Doppler frequency, and the number of resolvable paths on the packet cost for a single cell system are investigated by using Markov modeling for a multipath fading channel with a uniform power delay profile.

key words: *Packet transmission, closed-loop like power control, multipath fading*

1. Introduction

First and second generation mobile systems have been successfully launched and serviced in many countries around the world [1]. However, a shortage of capacity and continued demand for multimedia service have encouraged development of third generation systems, represented by International Mobile Telecommunications (IMT)-2000 [2], [3]. Owing to intensive efforts over several years, in the near future mobile communication will enter a new era in which users can communicate with each other with a single terminal anywhere in the world and enjoy multimedia services, including access to the Internet with a higher transmission speed.

Diverse services will be available. Therefore, different types of traffic must be handled in third generation systems, including voice, data, and image. All traffic is generally categorized as either stream or packet-based traffic [4]. Stream-based traffic, like voice, is transmitted continuously during a relatively long time interval where fast closed-loop signal-to-interference ratio (SIR)-based transmit power control (TPC) can be adopted to maintain the received E_s/I_o level at a specified target value by compensation for fast-varying multipath fading. Here E_s/I_o denotes the ratio of signal energy per modulation symbol to power spectrum density of average interference plus background noise. Our considered time interval is sufficient to allow smoothing of the instantaneous received signal power variations due to fading, but short enough to maintain intact the slow power variations due to shadowing. It is assumed that, when observed over the time interval, interference is approximated as Gaussian noise and, therefore, the sum of the background noise and the interference can be treated as new additive white Gaussian noise (AWGN). The average interference power varies slowly due to shadowing and variations in the path loss. On the other hand, packet-based traffic is transmitted during a short time (a single frame duration of 10 msec) without call and connection establishment procedures to avoid imposing an excessive burden on the network. In this case, no power control is applied during packet transmission and therefore, the received E_s/I_o may vary by packet due to fading, or even during reception of the packet. Accordingly, stream-based traffic and packet-based traffic are affected differently by multipath fading because of different power control schemes.

The performance of direct sequence code division multiple access (DS-CDMA) systems has been analyzed for stream-based traffic with SIR-based TPC [5]–[7]. Kim and Sung [5] introduced a methodology for capacity estimation in an SIR-based power-controlled system in a multiple cell environment and also extended the analysis to a multi-code CDMA system [6]. Recently Kim and Adachi [7] theoretically investigated the impact of multipath fading when antenna diversity reception is adopted. Some previous works [4], [8] have dealt with the performance of packet-based traffic. However, the impact of a power control scheme in a multipath fading environment has been ignored by simply assuming that either power control is perfect (as it is for stream-based traffic [4]), or only allowing compensation for the path loss and the slow shadowing [8]. Olofsson et al. [9] proposed a new power control scheme for packet transmission over DS-CDMA and investigated the impact of the scheme on access delay using simulations. The preamble is repeatedly transmit-

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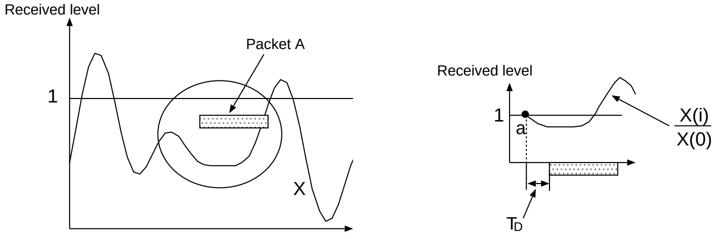
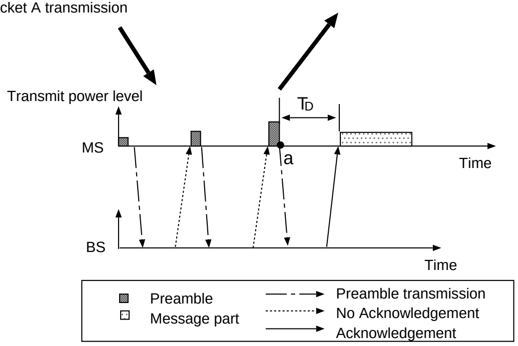


(a) Before Packet A transmission

(c) After successful preamble transmission



(b) Preamble transmission (Closed-loop-like power control)

Fig. 1 Packet transmission in a multipath fading environment.

ted prior to the data part with an increasing transmit power until successful reception at a BS. In this way, the transmit power is adjusted for transmission of the data part. This power control is herein referred to as a closed-loop like power control.

The performance of packet transmission using this closed-loop like power control depends on both a time-varying characteristic during the transmission of the data part and on the response delay from the end of preamble (channel measurement instant) and the beginning of data part. In [9], the impact of the time-varying characteristic of multipath fading was not investigated and only packet-based traffic was considered. Assuming closed-loop like power control, we consider a mixture of packet-based traffic and stream-based traffic. To see how packet-based traffic affects the reverse link capacity of the stream-based traffic, the concept of packet cost is introduced. Markov modeling [10]–[12] is used for a multipath fading channel with a uniform power delay profile where the states are determined by received E_s/I_o levels and the transition probabilities are calculated from level crossing rates (LCRs). In general, E_s/I_o levels and transition probabilities depend on the number of resolvable paths and the fading maximum Doppler frequency. We investigate the effects of the response delay, the fading maximum Doppler frequency, and the number of resolvable paths on the packet cost in a single cell environment (or in an isolated cell environment).

This paper is organized as follows. Sect. 2 introduces a closed-loop like power control for slotted packet transmission. Sect. 3 presents channel modeling and interference analysis. Sect. 4 analyzes the packet transmission performance and introduces the packet cost concept. Sect. 5 presents numerical examples and investigates the effects of the response delay, the fading maximum Doppler frequency, and the number of resolvable paths on the packet cost. Finally, Sect. 6 gives our conclusions.

2. Closed-loop like power control for slotted packet transmission

Figure 1 shows packet transmission in a multipath fading environment where X represents multipath fading experienced after Rake combining. When a mobile station (MS) has data (Packet A) to be sent, it first achieves synchronization with a BS, then obtains information regarding preamble scrambling code(s), available preamble signatures, and available access slots. The preamble signature specifies the channelisation code used for spreading of the message part, and the message part scrambling code has a one-to-one correspondence with the scrambling code used for the preamble part [18], [19]. In Fig. 1, the reverse link path loss and shadowing are assumed to be perfectly eliminated by open loop power control.

In order to compensate multipath fading, closed-loop like power control can be applied [9], [19] in which the preamble is transmitted with increasing power increments until an acknowledgement is received (see Fig. 1(b)). The channel gain due to multipath fading at the end of successful preamble transmission (point a) is here denoted as $X(0)$. It is assumed to take T_D sec from point a to the beginning of message part transmission. This time is called the response delay and corresponds to n_D symbols ($\overset{\triangle}{=} T_D \times$ symbol rate). This is a procedure of closed-loop like power control. For simplicity, it is assumed that the received E_s/I_o of the successful preamble needs to exactly meet the target level and that the acknowledgement can be received whenever the received E_s/I_o at point a is above the target level.

After receiving an acknowledgement, the MS transmits the corresponding message part. The transmit power level for message part can be determined based on the power level used for the successful preamble transmission. However, the transmit power of the message part is not necessarily the same as the transmit power of the preamble and may depend on the required packet error rate of the message part. Since the transmit power is constant during message part transmission, the received level varies according to multipath fading and therefore, the transmission may fail with a certain probability. We assume that only a single message part is associated with a successful preamble. Therefore, after a successful preamble only a single message part is transmitted. If multiple message parts are to be transmitted consecutively with the power level used for the first message part, the successive message parts may experience different received signal power levels and thus, different frame error rate. However, if several consecutive message parts exist, conventional fast TPC, as used for stream-based traffic, can be applied. Upon failure, packet transmission is retried in the same manner as for new packets after a random delay, until successful.

3. Channel modeling and interference analysis

The path loss and slow shadowing are assumed to be perfectly eliminated by open loop power control. Therefore, only multipath fading influences performance. We assume a uniform power delay profile with M resolvable propagation paths and a Rake combiner with M fingers.

3.1 Multipath fading channel

A DS-CDMA receiver can resolve the multipath channel into several frequency nonselective paths with discrete time delays of a multiple of chip duration T_c. It is assumed herein that each resolvable propagation path experiences the same path loss and the same shadowing. The equivalent lowpass impulse response of the multipath fading channel between the user of interest and the base station (BS) can be expressed as [13], [14]

$$h(t,\tau) = \sum_{l=0}^{M-1} \xi_l(t)\delta(\tau - \tau_l), \tag{1}$$

where $\xi_l(t)$ and τ_l are the complex-valued path gain and time delay of the l-th path, respectively, and $\delta(x)$ is the delta function. If a_l denotes $|\xi_l(t)|^2$, a_l satisfies the following condition:

$$\sum_{l=0}^{M-1} E[a_l] = 1. \tag{2}$$

Assuming a wide sense stationary uncorrelated scattering (WSSUS) channel model, a_l is exponentially distributed [15]. Since we are assuming a uniform power delay profile, the average value of a_l is given by

$$E[a_l] = \frac{1}{M}\ , 0 \le l \le M-1. \tag{3}$$

The multipath fading experienced after Rake combining with the M-finger can be represented by

$$X \overset{\triangle}{=} a_0 + \ldots + a_{M-1}. \tag{4}$$

Then, the probability density function (pdf) $f_X(x)$ of X follows the Erlang distribution:

$$f_X(x) = \frac{M^M}{(M-1)!} x^{M-1} e^{-Mx} U(x), \tag{5}$$

where $U(\cdot)$ is the step function.

3.2 Markov channel modeling

The best method to analyze the time-varying phenomenon due to multipath fading is using Markov modeling for the multipath fading channel [10]–[12]. Markov states are determined according to received E_s/I_o levels and the transition probabilities are calculated from LCRs. The LCR L_k is the expected number of times per second the received E_s/I_o passes upward (*or* downward) across a given level A_k.

Modeling steps are as follows:

1. Determine the K number of states, where state k is between the levels A_k and A_{k+1}, respectively, for $k = 0 \sim K-1$.
2. Obtain the LCR L_k, which depends on the fading maximum Doppler frequency and the number of resolvable paths.
3. Calculate the symbol-by-symbol state transition probabilities $t_{i,j}$'s assuming fading is slow enough to allow a constant level during a symbol duration.

First, Markov states are determined. If p_k is the probability that the channel is in state k, then p_k is given by [16]

$$p_k = \int_{A_k}^{A_{k+1}} f_X(x)dx. \tag{6}$$

We choose the levels A_k's so that all p_k's are equal, i.e., $1/K$ [10], then the level A_k can be obtained by

$$A_k = F_X^{-1}(k/K), \tag{7}$$

where $F_X^{-1}(x)$ denotes the inverse function of $F_X(x)$,

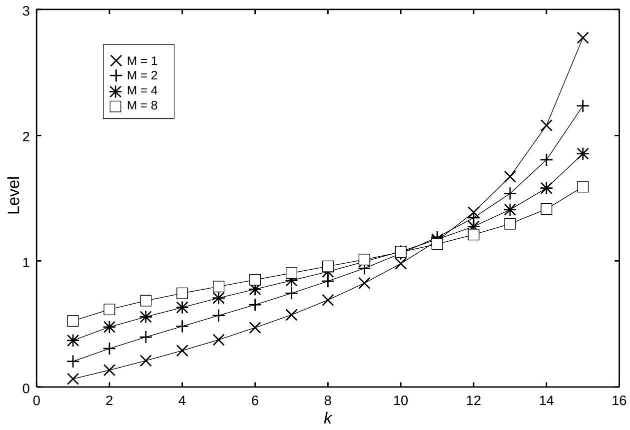


Fig. 2 The level A_k ($K = 16$).

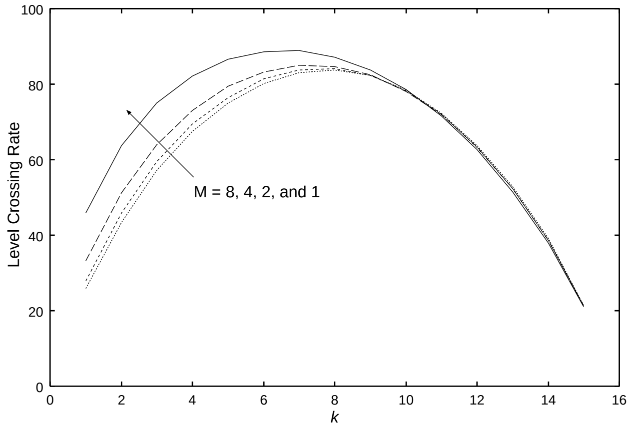


Fig. 3 The level crossing rate L_k ($f_m = 80$ Hz and $K = 16$).

and $F_X(x)$ is the cumulative distribution function (cdf) of X and is given by

$$\begin{aligned} F_X(x) &= \int_0^x f_X(x)dx \\ &= 1 - e^{-Mx} \sum_{k=0}^{M-1} \frac{(xM)^{M-1-k}}{(M-1-k)!}. \end{aligned} \tag{8}$$

A_0 and A_K are 0 and ∞, respectively. Figure 2 shows the levels for various values of M for a uniform power delay profile where K is set to 16. More multipaths results in less fluctuation due to the central limit theorem.

Using Monte Carlo simulations based on Jakes model [17] we can obtain L_k for various values of M. L_k is directly proportional to fading maximum Doppler frequency f_m for the same value of M. Figure 3 shows the LCR for $M = 1$, 2, 4, and 8 where $f_m = 80$ Hz and $K = 16$. With more multipaths, the received E_s/I_o crosses the lower level with a reduced frequency. Now, we define a $K \times K$ state transition probability matrix $\mathbf{T}$ with elements $t_{i,j}$ for i and $j = 0 \sim K-1$. $t_{i,j}$ is the state transition probability from state i to state j. $t_{i,i+1}(t_{i,i-1})$ can be approximated by the ratio of $L_{i+1}(L_i)$ and the average number of symbols in channel state i per second. We assume that fading is sufficiently slow so that a state only transits to an immediate neighbor state. Accordingly, $t_{i,j}$'s are given by [10]

$$t_{i,j} = \begin{cases} \frac{L_j}{R_s^i} & ,j = i+1 \ \& \\ & \quad 0 \le i \le K-2, \\ \frac{L_i}{R_s^i} & ,j = i-1 \ \& \\ & \quad 1 \le i \le K-1, \\ 1 - t_{0,1} & ,i = j = 0, \\ 1 - t_{K-1,K-2} & ,i = j = K-1, \\ 1 - t_{i,i+1} - t_{i,i-1} & ,i = j \ \& \\ & \quad 1 \le i \le K-2, \\ 0 & ,\text{otherwise}, \end{cases} \tag{9}$$

where R_s^i is defined as $R_s p_i$ with R_s being the symbol rate.

3.3 Signal power and average interference

When an acknowledgement for the preamble is received, the MS transmit power of the message part is adjusted. The BS received signal power at the end of preamble transmission becomes $S_0 = \beta S_{pp}$ where S_{pp} is the BS received signal power when the preamble is successfully received and β is the power difference that is required to meet the required packet error rate of the message part. The BS received signal power during message part reception may vary symbol by symbol and differ from S_0. The received E_s/I_o level of stream-based traffic can be kept constant at a target level owing to fast closed-loop SIR-based TPC. However, in packet transmission there is no power control during message part transmission and the transmit power is kept constant during that time. Thus, the message part to be transmitted may experience the multipath fading (see Fig. 1(c)). Hence, if the BS received power is set to S_0 at the end of the successful preamble reception (point a), the instantaneous received power $S_{pm}(i)$ at the BS after i symbols can be expressed as

$$S_{pm}(i) = S_0 \frac{X(i)}{X(0)} \triangleq \alpha(i) S_0, \tag{10}$$

where $X(i)$ represents the value of X after i-th transition with the condition that the initial value is $X(0)$ at point a. Letting B_m be the number of symbols per message part, the average received power $\overline{S}_{pm}$ during message part transmission is expressed as $\overline{S}_{pm} = \overline{\alpha} S_0$ where $\overline{\alpha}$ can be numerically obtained from

$$\overline{\alpha} \triangleq \sum_{d=0}^{K-1} p_d \frac{1}{B_m} \sum_{i=n_D}^{B_m-1+n_D} \sum_{k=0}^{K-1} \frac{e_k}{e_d} p_{k|d}(i), \tag{11}$$

where n_D is the response delay in symbols defined as the time difference between the end of the preamble and the beginning of the data part, and e_k denotes the average value of X in state k and is given by

$$e_k = \frac{1}{p_k}\int_{A_k}^{A_{k+1}} X f_X(x)dx. \tag{12}$$

$p_{k|d}(i)$ denotes the probability that $X(i)$ is in state k with a condition of $X(0)$ being in state d, Then, $p_{k|d}(i)$ for $i > 1$ can be calculated by

$$\mathbf{P}(i) = \mathbf{P}(i-1)\mathbf{T}, \tag{13}$$

where $\mathbf{P}(i)$ is a $1 \times K$ matrix with elements $p_{k|d}(i)$ with $p_{k|d}(0)$ being

$$p_{k|d}(0) = \begin{cases} 1 & \text{, for } k = d, \\ 0 & \text{, otherwise.} \end{cases} \tag{14}$$

4. Analysis of packet transmission performance

Error detection coding rather than channel coding is applied and binary phase shift keying (BPSK) modulation is assumed for simplicity. Hence, one symbol corresponds to one bit. A single cell system is assumed here.

4.1 Received E_s/I_o representation for stream-based traffic and packet-based traffic

Both stream-based and packet-based traffic are assumed to be transmitted at the same symbol rate R_s and each has the same spreading factor G defined as chip rate/symbol rate $= 1/(T_cR_s)$. N_s stream-based traffic users are in communication and the aggregated traffic load of packet-based traffic is denoted as ρ_a (defined as the number of packets per second multiplied by the packet length). Precisely, this is $\rho_a = \rho_n + \rho_r$, where ρ_n and ρ_r represent the traffic loads of new and retransmitted packets, respectively. A large number of steam-based traffic users are assumed in a single cell system ($N_s \gg 1$). Assuming SIR-based closed loop power control, the BS received signal power of stream-based traffic users is S_s, which is a random variable depending on the received interference level.

In the reverse link of a single cell system, (E_s/I_o) for a stream-based traffic user can be expressed as [5]–[7]

$$\left(\frac{E_s}{I_o}\right)_s \triangleq \frac{GS_s}{(N_s-1)S_s + \rho_a\overline{\alpha}S_0 + 1}, \tag{15}$$

where the signal power is normalized by the background noise power η_o with $\eta_o/2$ being the two-sided background noise power spectrum density. Thus, S_s and S_0 (and S_{pp}) hereafter denote the signal-to-noise power ratio (SNR). In (15), we neglect the impact of preamble transmission owing to a short transmission duration. Similarly, E_s/I_o value for successful preamble can be expressed as

$$\left(\frac{E_s}{I_o}\right)_{pp} = \frac{GS_{pp}}{N_sS_s + \rho_a\overline{\alpha}S_0 + 1}, \tag{16}$$

where S_{pp} is defined as the received SNR when the preamble is successfully received (see Sect. 3.3).

The traffic load ρ_a indicates that, on average, ρ_a packets are being transmitted at an arbitrary moment. With a large number of packet-based traffic users, the interfering packet-based traffic load for a packet-based traffic user of concern can be approximated as ρ_a. Since the effect of background noise is negligible for $N_s + \rho_a \gg 1$, the average interference in (15) and (16) and for message part are approximately the same and can be expressed as $N_sS_s + \rho_a\overline{\alpha}S_0$. Then, since $\alpha(i) = X(i)/X(0)$ in (10), the message part to be transmitted experiences

$$\left(\frac{E_s}{I_o}\right)_{pm} \approx \frac{GS_0\frac{X(i)}{X(0)}}{N_sS_s + \rho_a\overline{\alpha}S_0} \triangleq \alpha(i)\gamma_{pm}, \tag{17}$$

where γ_{pm} represents the E_s/I_o target associated with the data part. Assuming that $\left(\frac{E_s}{I_o}\right)_{pp}$ in (16) is maintained at a target value of γ_{pp} through closed-loop like power control, the value of β (introduced in Sect. 3.3) can be obtained as $\beta = \gamma_{pm}/\gamma_{pp}$ because $S_0 = \beta S_{pp}$.

4.2 Packet error probability and number of transmissions

We can calculate the average packet error probability P_p by considering the variation of $(E_s/I_o)_{pm}$, which follows $\alpha(i)$ during message part transmission. First, let k_i $(0 \le k_i < K)$ denote the state of $X(i)$ and accordingly, k_0 is the state of $X(0)$. Then, the state at the beginning of message part transmission becomes k_{n_D}. If $\mathbf{k} \triangleq (k_0, k_{n_D}, \ldots, k_{n_D+B_m-1})$, $\mathbf{k}$ represents the transition path during packet transmission. The probability that the packet transmission follows a path $\mathbf{k}$ is given by $p_{k_0}p_{k_{n_D}|k_0}(n_D)\prod_{i=n_D+1}^{n_D+B_m-1} t_{k_{i-1},k_i}$. Along the path, the message part endures bit error probabilities of $P_b(k_i)$ in state k_i $(n_D \le i < n_D + B_m)$, which are obtained by

$$P_b(k_i) \triangleq Q\left(\sqrt{2\gamma_{pm}\frac{e_{k_i}}{e_{k_0}}}\right), \tag{18}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-y^2/2}dy$. Then, the average packet error probability P_p can be expressed as

$$P_p = 1 - \sum_{k_0=0}^{K-1}\sum_{k_{n_D}=0}^{K-1}\cdots\sum_{k_{n_D+B_m-1}=0}^{K-1} P_{np}(\mathbf{k}), \tag{19}$$

where $P_{np}(\mathbf{k})$ is the probability of no message part error for a path $\mathbf{k}$ and can be calculated as

$$P_{np}(\mathbf{k}) = p_{k_0}p_{k_{n_D}|k_0}(n_D)(1 - P_b(k_{n_D}))$$

$$\prod_{i=n_D+1}^{n_D+B_m-1} t_{k_{i-1},k_i}(1-P_b(k_i)). \tag{20}$$

Since the packet is retransmitted until successful, the average number $\overline{N}_{tr}$ of transmissions per message part is

$$\overline{N}_{tr} = \sum_{i=1}^{\infty} i P_p^{i-1}(1-P_p) = \frac{1}{1-P_p}. \tag{21}$$

Hence, ρ_a can be rewritten as

$$\rho_a = \rho_n\left(1+\frac{\rho_r}{\rho_n}\right) = \frac{\rho_n}{1-P_p}. \tag{22}$$

4.3 Cost

From (15) and (17), $S_0/S_s \approx \gamma_{pm}/\gamma_s$ and (15) can be rewritten as

$$N_s = \frac{G}{\gamma_s} - \frac{\rho_n\overline{\alpha}}{1-P_p}\frac{\gamma_{pm}}{\gamma_s}, \tag{23}$$

where γ_s is the E_s/I_o target for stream-based traffic. For a given ρ_n and a target γ_s, the value N_s depends on γ_{pm} and P_p. Based on (23), γ_{pm} and P_p have a trade-off relationship. If γ_{pm} increases, packet error decreases and accordingly, ρ_a decreases because of fewer retransmissions. However, a large value of γ_{pm} causes significant interference for other users and therefore, the link capacity of the stream-based traffic is decreased, which is defined as $N_s+\rho_n$. To analyze this trade-off relationship we introduce the concept of packet cost, which is defined as $\frac{\overline{\alpha}}{(1-P_p)}\frac{\gamma_{pm}}{\gamma_s}$ from (23). The packet cost indicates the relative impact of a new packet-based traffic user on link capacity compared to a stream-based traffic user. A new packet-based traffic user causes a larger impact on the link capacity, by a factor of packet cost, than a stream-based traffic user. A lower packet cost provides a higher stream-based traffic capacity. Therefore, the minimum packet cost maximizes the number of supportable stream-based traffic users for given values of G, γ_s, and ρ_n. Due to the trade-off relationship between γ_{pm} and P_p, an optimum value exists for γ_{pm} that minimizes the packet cost.

5. Numerical examples

Table 1 shows the system parameters, which are assumed unless otherwise stated. The chip rate is 4.096 Mcps and the symbol rate is fixed at 32 ksps. Accordingly, the spreading factor G is 128. Error detection coding rather than channel coding is applied and BPSK modulation is assumed for simplicity. The target $(E_s/I_o)_s$ level, γ_s, of stream-based traffic is calculated to be 6.79 dB to satisfy $Q(\sqrt{2\gamma_s}) \le 10^{-3}$ with no channel coding. A 1 msec preamble and a 10 msec message part are assumed. In a slotted mode the slot length is set to 1.25 msec and hence, there are 8 slots in a 10 msec frame duration. The idle time of length 0.25 msec allows for processing of the preamble detection.

Table 1 System parameters.

G	128
R_s	32 ksps
$1/T_c$	4.096 Mcps
B_m	320 symbols
γ_s	6.79 dB
f_m	80 Hz
K	16 states
M	4 paths

Table 2 shows the value of $\overline{\alpha}$ for various sets of (M,f_m) and various values of n_D where K is set to 16. Since 1 msec preambles are transmitted in a slotted mode with a 1.25 msec slot, the delay to the next slot is 8 symbols. Similarly, the delay to the next frame is 328 symbols. Faster and deeper fading leads to a larger $\overline{\alpha}$. As the response delay increases, multipath fading during packet transmission becomes less correlated with $X(0)$, resulting in a larger value of $\overline{\alpha}$ results. Even though using a large number of Markov states guarantees a more exact result, $K = 16$ was used to reduce the computational time.

The computational time and power required for an average packet error probability evaluation is prohibitive for large values of K and B_m. Therefore, an alternate approximation method is required. Reducing the number of transitions by partitioning all transitions into a small number of clusters can reduce the computational load. The channel state at the beginning of cluster i is assigned to the state of cluster i and the channel is assumed to remain at the same state through the duration of the cluster. If $2n+1$ clusters are considered for the message part, then first $B_m/4n$ states belong to cluster 0, $\widehat{k}_0$, and next $B_m/2n$ states belong to cluster 1, $\widehat{k}_1$, …, and the final $B_m/4n$ states belong to cluster $2n$, $\widehat{k}_{2n}$. Assuming 5 clusters, since B_m is 320 symbols, k_0 to k_{39} belong to $\widehat{k}_0$, k_{40} to k_{119} belong to $\widehat{k}_1$, …, and k_{280} to k_{319} belong to $\widehat{k}_4$. The cluster-to-cluster transition probability $p_{\widehat{k}_j|\widehat{k}_i}(n)$, which corresponds to the probability that the channel state is changed from $\widehat{k}_i$ to $\widehat{k}_j$ after n symbol transitions, can be obtained from (13). Then, (19) can be approximated as

$$P_p \approx 1 - \sum_{k_0=0}^{K-1}\sum_{\widehat{k}_0=0}^{K-1}\cdots\sum_{\widehat{k}_4=0}^{K-1} p_{k_0}\, p_{\widehat{k}_0|k_0}(n_D)\prod_{i=0}^{4}\widehat{P}_{np}(i), \tag{24}$$

where

$$\widehat{P}_{np}(i) = \begin{cases} p_{\widehat{k}_1|\widehat{k}_0}(40)(1-P_b(\widehat{k}_0))^{40} & ,i=0 \\ p_{\widehat{k}_{i+1}|\widehat{k}_i}(80)(1-P_b(\widehat{k}_i))^{80} & ,i=1,2,3 \\ (1-P_b(\widehat{k}_4))^{40} & ,i=4. \end{cases} \tag{25}$$

Table 2 The value of $\overline{\alpha}$ for various sets of (M,f_m) and various values of n_D, where K is set to 16.

n_D (symbols)	8 (next slot)	88 (3rd slot)	328 (next frame)	648 (2nd frame)
(8,80 Hz)	1.03	1.04	1.067	1.1
(4,80 Hz)	1.064	1.089	1.15	1.20
(2,80 Hz)	1.16	1.224	1.38	1.53
(1,80 Hz)	1.54	1.77	2.37	2.98
(4,8 Hz)	1.008	1.012	1.023	1.036
(4,160 Hz)	1.11	1.15	1.22	1.27

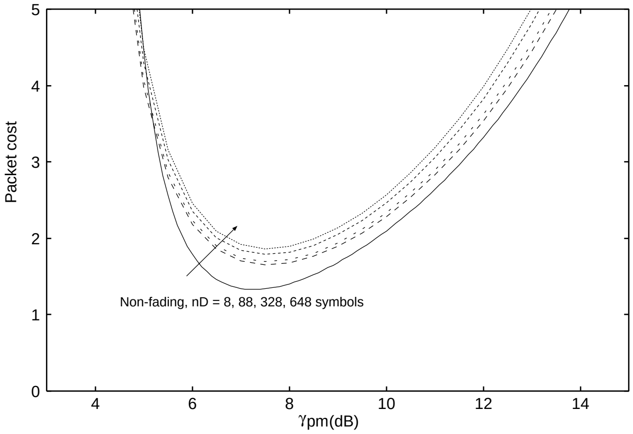


Fig. 4 The effect of the response delay n_D ($f_m = 80$ Hz and $M = 4$).

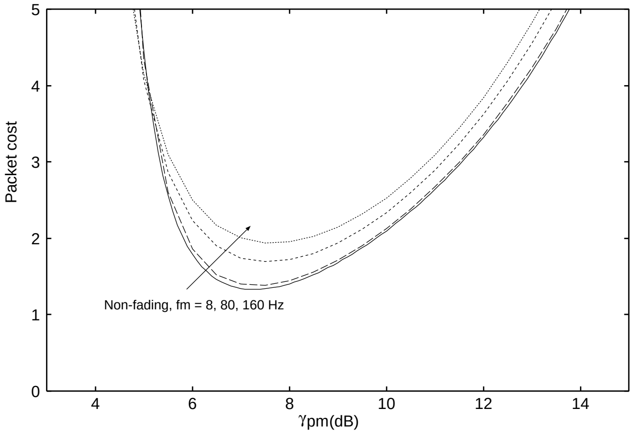


Fig. 5 The effect of the fading maximum Doppler frequency f_m ($M = 4$ and $n_D = 88$ symbols).

5.1 Effect of the response delay

Figure 4 shows the packet cost versus γ_{pm} for various values of the response delay n_D where $M = 4$ and $f_m = 80$ Hz. An optimum value for γ_{pm} exists that minimizes the packet cost (from 4.3). As indicated in Table 2, multipath fading values during packet transmission and at measurement moment become less correlated with each other for a longer response delay. Hence, a larger value of n_D results in a higher minimum packet cost. When $n_D = 88$ symbols, the minimum packet cost is 1.7 at $\gamma_{pm} = 7.5$ dB. However, if n_D is increased to 648 symbols (the message part is transmitted two frames later after sending a successful preamble) the minimum packet cost becomes 1.86 at the same value of γ_{pm}. The optimum γ_{pm} is insensitive to n_D and f_m, and is approximately 7.5 dB (see the following two subsections). This finding indicates that, at the BS receiver, the acknowledgement for the preamble should be sent to the MS when the preamble with $E_s/I_o > \gamma_{pp} = 7.5\,\text{dB} - 10\log\beta$ is received.

5.2 Effect of the fading maximum Doppler frequency

Figure 5 shows the effect of the fading maximum Doppler frequency f_m where $M = 4$. Compared to the non-fading case, the packet costs for $f_m = 80$ and 160 Hz are 28% and 46% larger, respectively. When $M = 4$ and $n_D = 88$ symbols, the minimum packet cost is 1.2 if $f_m = 8$ Hz, but the cost increases as f_m becomes larger and approaches 2 if $f_m = 160$ Hz. If fading is sufficiently slow, since closed-loop like TPC performs as well as closed-loop TPC, a single packet transmission is nearly equivalent, on average, to one stream-based traffic user when observed during the packet transmission period. However, as fading becomes faster, since closed-loop like TPC cannot compensate for fading variations, a large received signal value is received at a BS, resulting in significant interference to the stream-based traffic user. Therefore, a single packet transmission is equivalent, on average, to more than one stream-based traffic user. The optimum point remains at 7.5 dB as f_m changes from 8 Hz to 160 Hz. As γ_{pm} increases and approaches the optimum value, the packet cost decreases rapidly, but the cost gradually increases after γ_{pm} passes the optimum point.

5.3 Effect of the number of resolvable paths

Figure 6 plots the packet cost as a function of γ_{pm} for $M = 1$, 2, 4, and 8 where $f_m = 80$ Hz. The optimum γ_{pm} remains at 7.5 dB irrespective of M. The fluctuation in the received $(E_s/I_o)_{pm}$ becomes smaller for a larger value of M due to the increasing Rake combining effect, which improves the packet error performance and accordingly, reduces the packet cost. Compared to the minimum packet cost of 1.7 where $M = 4$, the

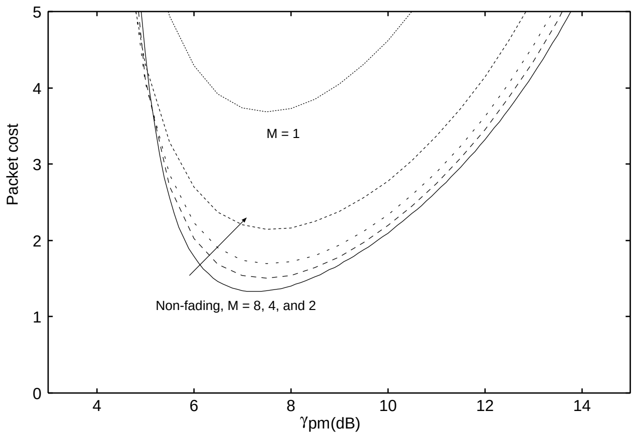


Fig. 6 The effect of the number M of multipaths ($f_m = 80\,\text{Hz}$ and $n_D = 88$ symbols).

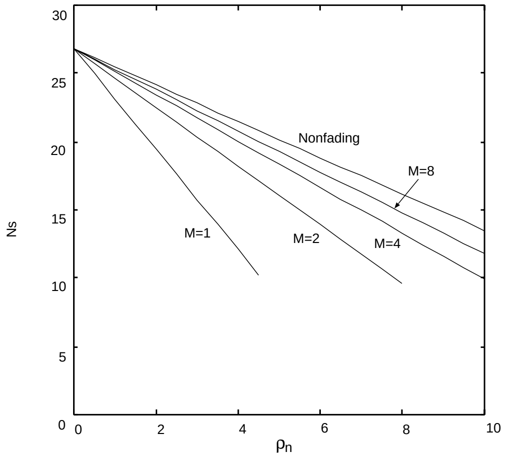


Fig. 7 The admissible regions: N_s versus ρ_n for various fading cases ($f_m = 80\,\text{Hz}$ and $n_D = 88$ symbols).

packet cost increases to 2.2 and 3.7 for $M = 2$ and 1, respectively. This implies that when a smaller number of multipaths are used for a Rake receiver, larger interference results and accordingly, packet transmission consumes more of the link capacity of the stream-based traffic.

5.4 Admissible region

Figure 7 shows the admissible regions needed to guarantee the required error performance for various fading cases where $f_m = 80\,\text{Hz}$, $n_D = 88$ symbols, and the minimum packet costs were assigned from Fig. 6. A larger packet cost implies that more interference is generated by packet-based traffic compared to stream-based traffic. Accordingly, the number of admissible stream-based traffic users is restricted by packet transmissions, which can be well characterized by packet cost. In the figure, the slopes of the admissible region boundaries are determined by packet cost.

6. Conclusions

The different impacts of packet-based traffic and stream-based traffic were investigated in a multipath fading environment with a uniform power delay profile, which is primarily induced by different power control schemes adopted in DS-CDMA systems. Perfect SIR-based TPC was assumed for stream-based traffic, while closed-loop like power control was assumed for packet-based traffic. Therefore, the message part transmission power was determined from the transmission power of a successfully received preamble. The time-varying channel was characterized using a Markov channel model based on the received E_s/I_o level and the LCRs. We introduced the concept of packet cost and investigated the impacts of the response delay (in symbols), defined as a time difference between the end of preamble and the beginning of the message part, the fading maximum Doppler frequency f_m, and the number M of resolvable multipaths. Perfect Rake combining was assumed even though in practice coherent Rake combining is quite difficult to achieve because the power of each resolved path is weak and the accuracy of channel estimation is degraded for a large value of M.

The optimum target E_b/I_o, γ_{pm}, for reception of the preamble was determined to maximize the number of supportable stream-based traffic users for a given traffic ρ_n of new packets (excluding the retransmitted packets). The value remained at the same level of $\gamma_{pm} = 7.5\,\text{dB}$, irrespective of the response delay, f_m, and M. However, the packet cost at optimum target E_b/I_o differs according to the response delay, f_m, and M. Therefore, the impact of packet-based traffic differs as well. The packet transmission impact is between 1 and 2 stream-based traffic users if f_m is below 160 Hz and M is larger than 1. The acknowledgement of the preamble at the BS can be sent to the MS for a preamble with $E_s/I_o > 7.5\,\text{dB} - 10\log\beta$ (β may depend on the required packet error rate).

For computational simplicity, a uniform power delay profile with the same number of fingers as multipaths was considered in this paper. However, the comparative results for an exponential power delay profile and for the case that the number of fingers is less than the number of resolvable paths can be estimated from [7]. Performance analysis for a multiple cell system and the imperfection of closed-loop like power control due to multipath fading are subject to further study. Also under study is the impact of channel coding.

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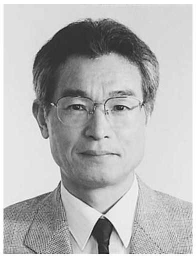

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