Serial Acquisition Performance of Single-Carrier and Multicarrier DS-CDMA Over Nakagami-m Fading Channels

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***Abstract*—In this paper, we investigate the issue of pseudo noise (PN) code acquisition in single-carrier and multicarrier (MC) direct-sequence code-division multiple-access (DS-CDMA) systems, when the channel is modeled by frequency-selective Nakagami-m fading. The PN code acquisition performance of single-carrier and MC DS-CDMA systems is analyzed and compared when communicating over Nakagami-m fading channels under the hypothesis of multiple synchronous states (H_1 cells) in the uncertainty region of the PN code. In the context of MC DS-CDMA, the code acquisition performance is evaluated, when the correlator outputs of the subcarriers associated with the same phase of the local PN code replica are noncoherently combined by using equal gain combining (EGC) or selection combining (SC) schemes. The performance comparison of the above mentioned schemes shows that the code acquisition performance of the MC DS-CDMA scheme, especially when using the EGC scheme, is more robust, than that of single-carrier DS-CDMA schemes communicating over the multipath Nakagami-m fading channels encountered. However, our code acquisition performance comparison also shows that if the detection threshold was set inappropriately, the performance might be degraded, even if the channel fading becomes less severe.**

***Index Terms*—Code acquisition, direct-sequence code-division multiple-access, equal gain combining, multicarrier transmission, Nakagami fading channel, selection combining.**

I. Introduction

PSEUDO noise (PN) code synchronization is the necessary first step in the receiver of direct-sequence code division multiple-access (DS-CDMA) systems, since data demodulation becomes possible only after code synchronization was established. Code synchronization is usually achieved in two steps: code acquisition for coarse code alignment and code phase tracking for fine alignment [1]. The focus of this paper is on initial code acquisition.

The code acquisition problem has attracted considerable research in recent years (see [2]–[15] and the references therein). The performance of code acquisition systems has been widely investigated over additive white Gaussian noise (AWGN) channels [5]–[10] and frequency nonselective, as well as frequency-selective Rayleigh or Rician fading channels [7]–[15], respectively. A more general fading channel model, which is often used in the literature for characterizing the fading statistics in a digital mobile-radio channel, is the Nakagami-m distribution [16]. This model is versatile and often fits the experimental data generated in a variety of fading environments—including urban as well as indoor radio propagation channels at a higher confidence level—than the Rayleigh and Rice distributions [17], [19]. Moreover, the Nakagami-m distribution function models a continuous transition from a Rayleigh fading channel to a Gaussian channel by varying a single parameter, namely m, from one to infinity [16]. Recently, the Nakagami fading channel model has been widely employed for the analysis of the error probability performance in wireless communication systems using different modulation schemes and with or without DS spreading [18]. However, in the context of initial synchronization, despite the above-mentioned advantages provided by the Nakagami-m distribution, the Nakagami fading channel model so far has not been invoked for the analysis of the initial synchronization performance of serial acquisition-assisted CDMA systems.

Our goal in this paper, therefore, is to quantify the performance of a serial search acquisition scheme over Nakagami-m fading channels, under the hypothesis that there are multiple synchronous states (H_1 cells) in the uncertainty region of the PN code [13]. Specifically, the acquisition performance of a serial search acquisition scheme is evaluated and compared for both single-carrier DS-CDMA systems and multicarrier DS-CDMA (MC DS-CDMA) systems, since MC DS-CDMA transmission schemes have been proposed, in order to achieve further advantages in terms of bandwidth efficiency, frequency diversity, reduced complexity parallel signal processing, and interference rejection capability in high data-rate transmissions [20], [23]–[26]. The parallel code acquisition performance of a MC DS-CDMA system has been investigated in [10], when each subcarrier signal is modeled as nonfading or flat Rayleigh fading, and with or without partial interference. In a MC DS-CDMA system considered in [24], the transmitted data bits are serial-to-parallel converted to a number of parallel streams and each stream is transmitted on a separate subcarrier, as portrayed in Fig. 1. In contrast to the MC DS-CDMA scheme considered in [10]—where each subcarrier's signal was subjected to frequency-nonselective fading—in the MC DS-CDMA system considered here, frequency-selective fading may be encountered by the signals transmitted over a given subcarrier [24], which consequently results in multiple so-called H_1 cells in the uncertainty region of the PN code and in the so-called multiple H_1 cell hypothesis [13]. However,

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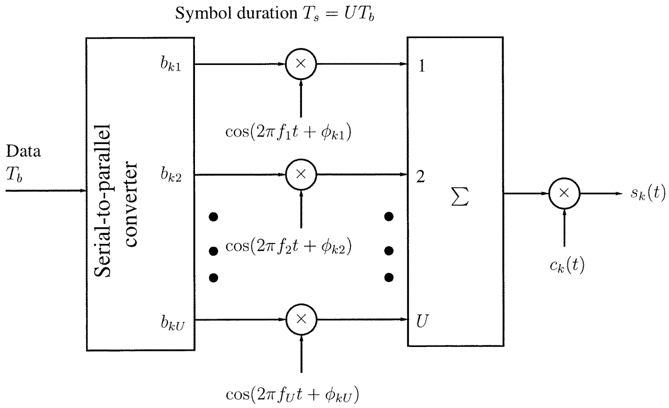


Fig. 1. The kth user's transmitter schematic for the generalized MC DS-CDMA system.

since in many CDMA systems the transmitter aids the initial acquisition by transmitting the phase-coded carrier signal without data modulation, consequently, in a MC DS-CDMA scenario, the outputs of the noncoherent subcarrier correlators associated with the same phase of the local PN code replica can be combined, as shown in [10]. Hence, in our analysis, as in [10], noncoherent equal gain combining (EGC) and selection combining (SC) schemes are investigated and their performance is compared to that of the equivalent single-carrier DS-CDMA scheme over frequency-selective Nakagami-m fading channels.

The remainder of this paper is organized as follows. In Section II, the MC DS-CDMA system is analyzed as well as the Nakagami-m fading channel model are described in more detail. Section III describes the serial search acquisition scheme as well as the equation quantifying the mean acquisition time. In Section IV, we analyze the statistics of the decision variables associated with both the EGC and SC schemes, while in Section V, we derive the overall miss probability and the false alarm probability. Our numerical results and comparisons are outlined in Section VI, and finally, our conclusions are offered in Section VII.

II. System Description

The transmitter schematic of the kth user is shown in Fig. 1 for the MC DS-CDMA system considered, which can be viewed as the simplified transmitter schematic of the MC DS-CDMA schemes studied in [20], [23]–[26]. For the MC DS-CDMA system using serial-to-parallel conversion [23], [24], the transmitted signal of user k can be expressed as

$$s_k(t) = \sum_{u=1}^{U} \sqrt{\frac{2P}{U}} b_{ku}(t) c_k(t) \cos(2\pi f_u t + \phi_{ku}) \quad (1)$$

where P represents the transmitted power of the MC DS-CDMA signal, while $\{b_{ku}(t)\}, c_k(t), \{f_u\}$, and $\{\phi_{ku}\}$ represent the data stream, the DS spreading waveform, the subcarrier frequency set and the phase angles introduced in the carrier modulation process. The data stream's waveform $b_{ku}(t) = \sum_{i=-\infty}^{\infty} b_{ku} P_{T_s}(t - iT_s)$ consists of a sequence of mutually independent rectangular pulses of duration $T_s = UT_b$ and of amplitude $+1$ or -1 with equal probability, where T_b represents the bit duration of the binary data before serial-to-parallel conversion. The spreading sequence $c_k(t) = \sum_{j=-\infty}^{\infty} c_{kj} P_{T_c}(t - jT_c)$ denotes the signature sequence waveform of the kth user, where c_{kj} assumes values of $+1$ or -1 with equal probability, while $P_{T_c}(t)$ is the rectangular chip waveform, which is defined over the interval $[0, T_c)$.

Let $N = T_s/T_c$ be the spreading gain of the subcarrier signals in the generalized MC DS-CDMA system and $N_1 = T_b/T_{c1}$ be the spreading gain of a corresponding single-carrier DS-CDMA system, where T_{c1} represents the chip duration of the corresponding single-carrier DS-CDMA signal. In the following analysis—for the sake of simplicity—we assume that there exists no spectral overlap between the spectral main-lobes of two adjacent subcarriers in the MC DS-CDMA system. Moreover, we assume that each subcarrier signal occupies an equal bandwidth and the total system bandwidth is evenly divided among the U number of subcarriers. Hence, we have $2/T_{c1} = U \times 2/T_c$ or $T_c = UT_{c1}$ and $N_1 = N$, since $T_s = UT_b$. Based on the above assumption, we can infer that both the MC and the corresponding single-carrier DS-CDMA system have the same information rate of $1/T_b$ and the same system bandwidth of $2/T_{c1}$, which allows their direct comparison in the forthcoming discourse.

We assume that the channel between the kth transmitter and the corresponding receiver is a multipath Nakagami-m fading channel [16], that the system supports K users and that all users have the same number of subcarriers, namely U. Moreover, we assume that the first user is the one that requires initial synchronization, while the other users are synchronized and reached the data transmission stage. Furthermore, we assume that all users have the same average received power. Consequently, when K signals obeying the form of (1) are transmitted over the multipath Nakagami-m fading channels, the received signal at the base station can be expressed as

$$r(t) = \sum_{k=1}^{K} \sum_{u=1}^{U} \sum_{l_p=0}^{L_p-1} \sqrt{\frac{2P}{U}} \alpha_{ul_p}^{(k)} b_{ku}(t - \tau_{kl_p}) c_k(t - \tau_{kl_p}) \cos\left(2\pi f_u t + \varphi_{ul_p}^{(k)}\right) + n(t) \quad (2)$$

where $\varphi_{ul_p}^{(k)}$ is due to the carrier modulation and the fading channel, $n(t)$ represents the AWGN with zero mean and double-sided power spectral density of $N_0/2$. Moreover, the multipath attenuations $\{\alpha_{ul_p}^{(k)}\}$ in (2) are independent Nakagami random variables with a probability density function (PDF) of [16] and [18]

$$p\left(\alpha_{ul_p}^{(k)}\right) = M\left(\alpha_{ul_p}^{(k)}, m, \Omega_{ul_p}^{(k)}\right)$$
$$M(R, m, \Omega) = \left(\frac{m}{\Omega}\right)^m \frac{2R^{2m-1}}{\Gamma(m)} \exp\left(-\frac{mR^2}{\Omega}\right) \quad (3)$$

where $\Gamma(\cdot)$ is the gamma function [27], m is the Nakagami-m fading parameter, while $\Omega_{ul_p}^{(k)}$ in (3) is the second moment of $\alpha_{ul_p}^{(k)}$. We assume a negative exponentially decaying multipath intensity profile (MIP) distribution given by $\Omega_{ul_p}^{(k)} = \Omega_{u0}^{(k)} e^{-\eta l_p}, \eta \geq 0$, where $\Omega_{u0}^{(k)}$ is the average signal strength corresponding to the first resolvable path and η is the rate of average power decay. For more detailed information concerning the Nakagami distribution, readers are referred to the excellent contribution by Simon and Alouini [18].

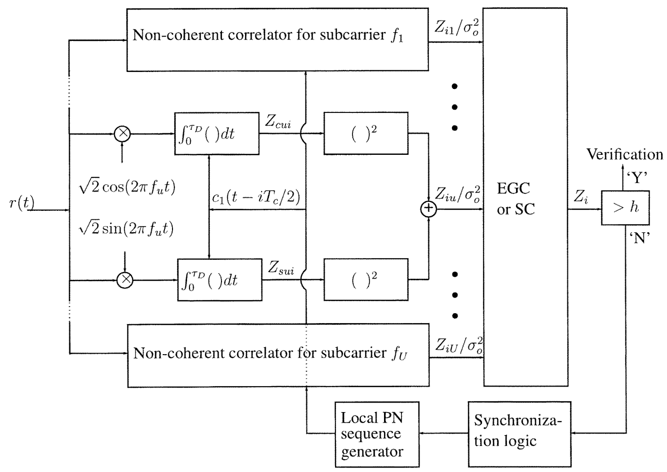


Fig. 2. Block diagram of generating the decision variable Z_i for the MC DS-CDMA code-acquisition system.

III. Serial Search Acquisition

The block diagram of the serial search mode and the detection mode designed for the MC DS-CDMA system is shown in Fig. 2. The received signal is first down converted into in-phase (I) and quadrature (Q) components associated with each subcarrier. Let us assume that the search step size is $T_c/2$. For each subcarrier a pair of I-Q correlators perform correlation between the locally generated PN sequence $c(t-iT_c/2)$ and the I as well as the Q baseband signals in Fig. 2, while integration takes place over the interval dwell time of τ_D seconds. The outputs of the I-Q correlators are then squared and summed, in order to generate the output variable $Z_{iu}, u=1,2,\ldots,U$ in Fig. 2.

We assume that the transmitter aids the initial synchronization by transmitting the phase-coded carrier signal without data modulation at the commencement of each transmission. In the MC DS-CDMA acquisition scheme of Fig. 2, since all subcarriers employ the same spreading code, as shown in Fig. 1, and since we have assumed that no data modulation is imposed during the acquisition stage, the outputs of the U noncoherent subcarrier correlators seen in Fig. 2 and associated with the same phase of the local despreading code can be combined. Again, in this contribution two noncoherent combining schemes—namely EGC and SC—will be investigated. Let $Z_i, i=1,2,\ldots$ be the output of the combiner of Fig. 2, which represents the decision variable. Let h in Fig. 2 be a decision threshold. Then, the search and detection mode can be described as follows. Whenever the decision variable Z_i exceeds the threshold h, the system assumes that the corresponding delay of the locally generated PN sequence is the correct delay and proceeds to the verification mode. Otherwise, if Z_i does not exceed h, the relative phase of the locally generated PN sequence is readjusted, in order to update the decision variable Z_i, and the above process is repeated. Note that, the verification mode is usually used to confirm a stronger decision concerning the correct delay assumed by the search mode [1], an issue not analyzed in this paper.

The generalized asymptotic equation for the mean acquisition time of serial search acquisition schemes has been given in [13] and [15], which can be expressed as

$$\overline{T}_{\text{acq}} \approx \frac{[1+P_M(\lambda)](1+JP_{\text{FA}})}{2[1-P_M(\lambda)]}(q\tau_D) \tag{4}$$

where q represents the total number of states in the uncertainty region of the PN sequence, P_{FA} represents the false alarm probability of an asynchronous state (H_0 cell), while $J\tau_D$ represents the "penalty time" associated with noticing that there is a false alarm and with re-entering the search mode. Furthermore, $P_M()$ represents the overall miss probability of the search mode, i.e., that of the event, when none of the correctly synchronized phases have been found during the tests over the whole uncertainty region. Let us assume that there are $\lambda\, H_1$ cells in the total of q number of states and that their corresponding detection probabilities are expressed as $\{P_{D_1}, P_{D_2}, \ldots, P_{D_\lambda}\}$. Assuming that the test of each cell is an independent event, the overall miss probability is defined as

$$P_M(\lambda) = \prod_{i=1}^{\lambda}(1-P_{D_i}). \tag{5}$$

Having described the search and detection mode as well as having given the equation quantifying the mean acquisition time, let us now derive the statistics of the decision variables.

IV. Decision Variable Statistics

The output variable of Fig. 2 matched to the subcarrier f_u can be expressed as

$$\begin{aligned} Z_{iu} &= Z_{\text{cui}}^2 + Z_{\text{sui}}^2 \\ &= \left[\int_0^{MT_c} r(t)c_1(t-iT_c/2)\sqrt{2}\cos(2\pi f_u t)\,dt\right]^2 \\ &\quad + \left[\int_0^{MT_c} r(t)c_1(t-iT_c/2)\sqrt{2}\sin(2\pi f_u t)\,dt\right]^2 \end{aligned} \tag{6}$$

where $i=1,2,3,\ldots$ and $u=1,2,\ldots,U$, while $M=\tau_D/T_c$ is an integer. Let us assume that the pull-in range of the code tracking loop used is $[-T_c/2, T_c/2)$. We assume that acquisition has occurred, whenever τ_{l_p} of the reference user in (2) and its estimate $i_{\text{est}}T_c/2$ obey the relationship of $|\tau_{1l_p} - i_{\text{est}}T_c/2| < T_c/2$, while the PN sequence is not acquired, whenever this condition does not hold. Then, upon assuming that the Gaussian approximation of the multipath interference and that of the multiple access interference can be invoked, and following the analysis of [15], it can be shown that both Z_{cui} and Z_{sui} can be approximated by Gaussian random variables having means given by $\sqrt{(P/U)}MT_c[(3/4)\alpha_{ul_p}\cos\varphi_{ul_p}]$ and $\sqrt{(P/U)}MT_c[(3/4)\alpha_{ul_p}(-\sin\varphi_{ul_p})]$ [15]—where the superscript of $k=1$ is deleted—if a H_1 cell is being tested, and zero, if a H_0 cell is being tested. Assuming that the MIP distribution given by $\Omega_{ul_p}^{(k)}$ is independent of the subcarrier index u and of the user index k, then, it can be shown that the variance for both Z_{cui} and Z_{sui} can be expressed as $\sigma_o^2 = (PM^2T_c^2)/(U)[([q(L_p,\eta)-1]\Omega_0)/(3M) + ((K-1)q(L_p,\eta)\Omega_0)/(3M) + (1)/(2M\gamma_c)]$, where $q(L_p,\eta) = (1-e^{-\eta L_p})/(1-e^{-\eta}), \gamma_c = E_c/N_0$ is the signal-to-noise ratio (SNR) per chip (SNR/chip), and $E_c = (PT_c)/(U) = PT_{c1}$ is the chip energy, which remains constant for MC DS-CDMA schemes using different values of U, but having the same transmission rate.

Let $Y_{iu} = Z_{iu}/\sigma_o^2, u = 1, 2, \ldots, U$ be the normalized output of the uth subcarrier associated with the ith phase. It can be readily shown that conditioned on α_{ul_p}, Y_{iu} becomes chi-square distributed [27] with two degrees of freedom, and its PDF can be expressed as

$$f_{Y_{iu}}(y|H_1, \gamma_{ul_p}) = \frac{1}{2}\exp\left(-\frac{y+\gamma_{ul_p}}{2}\right) + I_0\left(\sqrt{\gamma_{ul_p} y}\right), \qquad y \geq 0 \tag{7}$$

if a H_1 cell is being tested, where (8) and (9), shown at the bottom of the page hold. Note that, for single-carrier DS-CDMA, M in the above equation should be replaced by $M_1 = MU$, since in this case $M_1 = \tau_D/T_{c1} = MU$ is the number of chips within the integral dwell time τ_D. If a H_0 cell is being tested, then [27]

$$f_{Y_{iu}}(y|H_0) = \frac{1}{2}\exp\left(-\frac{y}{2}\right), \qquad y \geq 0. \tag{10}$$

Since $\{\alpha_{ul_p}\}$ are independent random variables obeying the Nakagami-m distribution of (3), then, with the aid of (3) it can be shown that the PDF of γ_{ul_p} defined in (8) can be expressed as

$$f(\gamma_{ul_p}) = \left(\frac{m}{\overline{\gamma}_c e^{-\eta l_p}}\right)^m \frac{\gamma_{ul_p}^{m-1}}{\Gamma(m)} \exp\left(-\frac{m\gamma_{ul_p}}{\overline{\gamma}_c e^{-\eta l_p}}\right), \quad \gamma_{ul_p} \geq 0. \tag{11}$$

A. Equal Gain Combining

For the MC DS-CDMA system using U number of subcarriers and EGC the U branches associated with the same phase of the local PN sequence are equally weighted and then added, in order to form the decision variables Z_i. As shown in Fig. 2, Z_i can be expressed as

$$Z_i = \sum_{u=1}^{U} Y_{iu}, \quad i = 1, 2, \ldots. \tag{12}$$

The PDF of Z_i associated with a H_1 cell or a H_0 cell can be readily derived following the philosophy of [22], which can be expressed as:

$$f_{Z_i}(y|H_1) = \frac{y^{U-1}\exp(-y/2)}{2^U(U-1)!\,(1+\overline{\gamma}_c e^{-\eta l_p}/2m)^{Um}} \times {}_1F_1\left(Um; U; \frac{\overline{\gamma}_c e^{-\eta l_p} y}{4m + 2\overline{\gamma}_c e^{-\eta l_p}}\right), \quad y \geq 0 \tag{13}$$

$$f_{Z_i}(y|H_0) = \frac{1}{2^U(U-1)!} y^{U-1}\exp\left(-\frac{y}{2}\right), \quad y \geq 0 \tag{14}$$

where ${}_1F_1()$ is the confluent hypergeometric function, which is defined as ${}_1F_1(a; b; x) = \sum_{k=0}^{\infty}((a)_k x^k)/((b)_k k!), b \neq 0, -1, -2, \ldots$, and $(a)_k = a(a+1)(a+2)\cdots(a+k-1), (a)_0 = 1$ [28]. However, ${}_1F_1(a; b; x)$ for $x >> 0$ and $a > b > 0$ has a very high value—the case in our analysis—which may result in an overflow in the corresponding numerical computations, hence it is usually difficult to achieve sufficient accuracy for the estimation of (13). This predicament can be resolved by substituting the relationship of ${}_1F_1(a; b; x) = e_1^x F_1(b-a; b; -x)$ [28] into (13), yielding

$$f_{Z_i}(y|H_1) = \frac{y^{U-1}\exp\left(-\frac{my}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{2^U(U-1)!\,(1+\overline{\gamma}_c e^{-\eta l_p}/2m)^{Um}} \times {}_1F_1\left(U(1-m); U; -\frac{\overline{\gamma}_c e^{-\eta l_p} y}{4m+2\overline{\gamma}_c e^{-\eta l_p}}\right) \quad y \geq 0 \tag{15}$$

which, for the cases considered in this paper, can be readily estimated using numerical approaches.[1] Furthermore, if a multipath Rayleigh fading channel model associated with $m = 1$ is considered, then, ${}_1F_1(0; b; x) = 1$ and (15) is reduced to

$$f_{Z_i}(y|H_1) = \frac{1}{(U-1)!\,(2+\overline{\gamma}_c e^{-\eta l_p})^U} y^{U-1} \times \exp\left(-\frac{y}{2+\overline{\gamma}_c e^{-\eta l_p}}\right), \quad y \geq 0. \tag{16}$$

B. Selection Combining

For a MC DS-CDMA scheme using U number of subcarriers and SC—where the subcarrier signal having the largest amplitude is selected for detection—the decision variable is defined as

$$Z_i = \max\{Y_{i1}, Y_{i2}, \ldots, Y_{iU}\} \tag{17}$$

where $\{Y_{iu}, u = 1, 2, \ldots, U\}$ are independent identically distributed (i.i.d.) random variables with the PDF characterized by (7), if a H_1 cell hypothesis is being tested, while by (10), if a H_0 cell hypothesis is being tested. Hence, for a H_0 cell the PDF of Z_i in (17) can be expressed after a number of manipulations as

$$f_{Z_i}(y|H_0) = \frac{d}{dy}\left[\int_0^y f_{Y_{iu}}(x|H_0)dx\right]^U = \frac{U}{2}\exp\left(-\frac{y}{2}\right)\left[1-\exp\left(-\frac{y}{2}\right)\right]^{U-1}, \quad y \geq 0. \tag{18}$$

[1]Since $(-n)_{n+1} = 0$, if n is a positive integer, then ${}_1F_1(-n, b, x)$ is the sum of only a limited number of terms, which can be expressed as ${}_1F_1(-n, b, x) = \sum_{k=0}^{n}((-n)_k x^k)/((b)_k k!)$. Therefore, if m is a positive integer, (15) consists of the sum of limited terms.

$$\gamma_{ul_p} = \frac{PM^2T_c^2\left[\frac{3}{4}\alpha_{ul_p}\cos\varphi_{ul_p}\right]^2 \Big/ U + PM^2T_c^2\left[\frac{3}{4}\alpha_{ul_p}(-\sin\varphi_{ul_p})\right]^2 \Big/ U}{\sigma_o^2} = \overline{\gamma}_c \cdot \frac{\alpha_{ul_p}^2}{\Omega_0} \tag{8}$$

and

$$\overline{\gamma}_c = \frac{9}{16}\left(\frac{1}{3M}[Kq(L_p,\eta)-1] + \frac{1}{2M\Omega_0\gamma_c}\right)^{-1}. \tag{9}$$

By contrast, if a H_1 cell hypothesis is being tested, the PDF of Z_i of (17) can be expressed after a number of manipulations as

$$\begin{aligned} f_{Z_i}(y|H_1) &= E\left\{\frac{d}{dy}\left[\int_0^y f_{Y_{iu}}(x|H_1,\gamma_{ul_p})\,dx\right]^U\right\} \\ &= \frac{d}{dy}\left[\int_0^y E\left\{f_{Y_{iu}}(x|H_1,\gamma_{ul_p})\right\}\,dx\right]^U \\ &= \frac{d}{dy}\left[\int_0^y\int_0^\infty f_{Y_{iu}}(x|H_1,\gamma_{ul_p})f(\gamma_{ul_p})d\gamma_{ul_p}\,dx\right]^U. \end{aligned} \tag{19}$$

Upon substituting the PDFs of (7) and (11) into the above equation, we obtain[2]

$$\begin{aligned} f_{Z_i}(y\,|\,H_1) = {} & \frac{U\exp\left(-\frac{my}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{2\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^m}[1-\mathcal{H}(y)]^{U-1} \\ & \times {}_1F_1\left(1-m;1;-\frac{\overline{\gamma}_c e^{-\eta l_p}y}{4m+2\overline{\gamma}_c e^{-\eta l_p}}\right), \quad y\geq 0, \end{aligned} \tag{20}$$

where

$$\begin{aligned} \mathcal{H}(y) = {} & 2^{m-1}\exp\left(-\frac{my}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right) \\ & \times\sum_{n=0}^{\infty}\sum_{k=0}^{n}\left(-\frac{\overline{\gamma}_c e^{-\eta l_p}}{2m}\right)^n \\ & \times\left(\frac{m}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)^{m+k-1}\frac{(1-m)_n y^k}{n!k!}. \end{aligned} \tag{21}$$

Furthermore, if $m = 1$, it can be shown that $\mathcal{H}(y) = \exp(-(y)/(2+\overline{\gamma}_c e^{-\eta l_p}))$, and (20) is reduced to

$$\begin{aligned} f_{Z_i}(y\,|\,H_1) = {} & \frac{U}{2+\overline{\gamma}_c e^{-\eta l_p}}\exp\left(-\frac{y}{2+\overline{\gamma}_c e^{-\eta l_p}}\right) \\ & \times\left[1-\exp\left(-\frac{y}{2+\overline{\gamma}_c e^{-\eta l_p}}\right)\right]^{U-1}, \quad y\geq 0. \end{aligned} \tag{22}$$

In this section, we have derived the statistics of the decision variables associated with both the EGC and SC schemes. With the aid of the PDFs derived in this section, in Section V, we derive the overall miss probability and the false alarm probability.

V. Probabilities of Detection and False Alarm

The overall miss probability is given by (5), where P_{D_i} represents the detection probability of a H_1 cell, which will be derived in our forthcoming discourse, λ represents the number of H_1 cells in the uncertainty region to be searched. We have assumed that the pull-in range of a code tracking-loop is $[-T_c/2, T_c/2)$ and the search step size is $T_c/2$. We further assume that a H_1 hit occurred, whenever the phase difference between the incoming PN sequence and the locally generated PN sequence is within the pull-in range of the code tracking-loop. However, any other phase difference between the incoming PN sequence and the locally generated PN sequence not following the above condition is assumed to be associated with H_0 cells. It can be readily shown that each resolvable path will contribute two H_1 cells: if one occurred at $|\tau_{ul_p} - (i_{\rm est}T_c)/(2)| < (T_c)/(2)$, then the other one occurred at $|\tau_{ul_p} - (i_{\rm est}T_c)/(2) + (T_c)/(2)| < (T_c)/(2)$ or at $|\tau_{ul_p} - (i_{\rm est}T_c)/(2) - (T_c)/(2)| < (T_c)/(2)$. Let the number of cells corresponding to the transmitted PN sequence be q and the number of resolvable paths associated with each subcarrier be L_p. Then, the total number of cells to be searched in the L_p-tap dispersive fading channel is $(q(T_c)/(2) + (L_p-1)T_c)/(T_c)/(2) = q + 2(L_p - 1)$, and the number of H_1 cells is $L_P T_c/(T_c)/(2) = 2L_p$, where $(L_p-1)T_c$ represents the maximum delay-spread of the L_p-tap fading channels. Bearing these in mind, let us now derive the overall miss probability and the false alarm probability in the context of both the EGC and SC schemes.

A. EGC

In order to derive the overall miss probability, the detection probability of each H_1 cell must be first obtained. For EGC the detection probability of a H_1 cell can be expressed as

$$P_{D_{l_p}} = \int_h^\infty f_{Z_{l_p}}(y|H_1)\,dy, l_p = 0,1,2,\ldots,L_p-1 \tag{23}$$

where h represents the decision threshold, $P_{D_{l_p}}$ represents the detection probability of the H_1 cell associated with the l_pth resolvable path, and $f_{Z_{l_p}}(y|H_1)$ is given by (13) or alternatively by (15). Upon substituting (15) into the above equation, it can be shown that

$$\begin{aligned} P_{D_{l_p}} = {} & \frac{\exp\left(-\frac{mh}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^{U(m-1)}} \\ & \times\sum_{n=0}^{\infty}\sum_{k=0}^{U+n-1}\left(-\frac{\overline{\gamma}_c e^{-\eta l_p}}{2m}\right)^n \\ & \times\left(\frac{m}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)^k\frac{(U-Um)_n h^k}{n!k!}. \end{aligned} \tag{24}$$

If m is a positive integer, we have $(U-Um)_{Um-U+1} = 0$ and, therefore, (24) represents the sum of limit terms, which can be expressed as

$$\begin{aligned} P_{D_{l_p}} = {} & \frac{\exp\left(-\frac{mh}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^{U(m-1)}} \\ & \times\sum_{n=0}^{U(m-1)}\sum_{k=0}^{U+n-1}\left(-\frac{\overline{\gamma}_c e^{-\eta l_p}}{2m}\right)^n \\ & \times\left(\frac{m}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)^k\frac{(U-Um)_n h^k}{n!k!}. \end{aligned} \tag{25}$$

Furthermore, if $m = 1$, (25) can be further simplified to

$$P_{D_{l_p}} = \exp\left(-\frac{h}{2+\overline{\gamma}_c e^{-\eta l_p}}\right)\sum_{k=0}^{U-1}\frac{1}{k!}\exp\left(-\frac{h}{2+\overline{\gamma}_c e^{-\eta l_p}}\right). \tag{26}$$

Since each resolvable path contributes two H_1 cells, as we discussed previously [15], and since the average detection prob-

[2]The average in (19), which is given by $\int_0^\infty f_{Z_{iu}}(x|H_1,\gamma_{ul_p}) f(\gamma_{ul_p})d\gamma_{ul_p}$, can be derived from (15) by setting $U = 1$.

ability in the context of these two H_1 cells is the same, according to (5) the overall miss probability of EGC can be expressed as

$$P_M(2L_p) = \prod_{l_p=0}^{L_p-1} (1 - P_{D_{l_p}})^2 \tag{27}$$

where $P_{D_{l_p}}$ is given by (24), (25), or (26).

According to the search and detection mode, the false alarm probability associated with a H_0 cell is defined as the probability of the event that the output decision variable corresponding to the H_0 cell exceeds the decision threshold, h, which can be expressed as

$$P_{\text{FA}} = \int_h^\infty f_{Z_i}(y|H_0)dy \tag{28}$$

where $f_{Z_i}(y|H_0)$ is given by (14). Upon substituting (14) into (28), the false alarm probability of EGC can be expressed as

$$P_{\text{FA}} = \exp\left(-\frac{h}{2}\right)\sum_{k=0}^{U-1}\frac{(h/2)^k}{k!}. \tag{29}$$

Finally, the mean acquisition time of the serial search mode for the MC DS-CDMA using EGC can be evaluated by substituting (27) and (28) and the other related parameters into (4).

B. Selection Combining

For SC the detection probability of a H_1 cell can be also expressed by (23) with $f_{Z_{l_p}}(y|H_1)$ given by (20). Upon substituting (20) into (23), the detection probability of $P_{D_{l_p}}, l_p = 0, 1, \ldots, L_p - 1$ can be expressed as

$$P_{D_{l_p}} = \int_h^\infty \frac{U\exp\left(-\frac{my}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{2\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^m} \times [1-\mathcal{H}(y)]^{U-1}{}_1F_1\left(1-m;1;-\frac{\overline{\gamma}_c e^{-\eta l_p}y}{4m+2\overline{\gamma}_c e^{-\eta l_p}}\right)dy. \tag{30}$$

However, it seems that there exists no closed-form formula for the detection probability of (30), which can only be estimated hence relying upon a numerical approach. However, if $m = 1$, with the aid of (22), we have

$$\begin{aligned} P_{D_{l_p}} &= 1 - \left[1 - \exp\left(-\frac{h}{2+\overline{\gamma}_c e^{-\eta l_p}}\right)\right]^U \\ &= \sum_{k=1}^{U}(-1)^{k+1}\binom{U}{k}\exp\left(-\frac{kh}{2+\overline{\gamma}_c e^{-\eta l_p}}\right). \end{aligned} \tag{31}$$

The overall miss probability for SC can be expressed as in (27) with $P_{D_{l_p}}$ given by (30) or (31) for $m = 1$.

The false alarm probability associated with the SC can be expressed as in (28), with $f_{Z_i}(y|H_0)$ given by (18). Upon substituting (18) into (28), we obtain that

$$\begin{aligned} P_{FA} &= 1 - \left[1 - \exp\left(-\frac{h}{2}\right)\right]^U \\ &= \sum_{k=1}^{U}(-1)^{k+1}\binom{U}{k}\exp\left(-\frac{kh}{2}\right). \end{aligned} \tag{32}$$

Finally, the mean acquisition time of the serial search mode for the MC DS-CDMA system using SC can be evaluated by substituting (27) associated with (30), and (32) as well as the other related parameters into (4).

So far, we have derived the equations required for computing the mean acquisition time of the MC DS-CDMA scheme associated with EGC and SC. For the single-carrier DS-CDMA benchmarker scheme, the mean acquisition time can also be computed from the corresponding equations of EGC or SC by setting $U = 1$. Specifically, by setting $U = 1$ in (24) or (30), it can be shown that the detection probability with respect to the l_pth resolvable path can be expressed as

$$\begin{aligned} P_{D_{l_p}} = &\frac{\exp\left(-\frac{mh}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^{m-1}} \\ &\times \sum_{n=0}^{\infty}\sum_{k=0}^{n}\left(-\frac{\overline{\gamma}_c e^{-\eta l_p}}{2m}\right)^n \\ &\times \left(\frac{m}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)^k \frac{(1-m)_n h^k}{n!k!} \end{aligned} \tag{33}$$

where $l_p = 0, 1, \ldots, L_1 - 1$, and L_1 represents the number of resolvable paths of the single-carrier DS-CDMA signals. If m is a positive integer, we have

$$\begin{aligned} P_{D_{l_p}} = &\frac{\exp\left(-\frac{mh}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)}{\left(1+\overline{\gamma}_c e^{-\eta l_p}/2m\right)^{m-1}} \\ &\times \sum_{n=0}^{m-1}\sum_{k=0}^{n}\left(-\frac{\overline{\gamma}_c e^{-\eta l_p}}{2m}\right)^n \\ &\times \left(\frac{m}{2m+\overline{\gamma}_c e^{-\eta l_p}}\right)^k \frac{(1-m)_n h^k}{n!k!}. \end{aligned} \tag{34}$$

Furthermore, if $m = 1$, we have

$$P_{D_{l_p}} = \exp\left(-\frac{h}{2+\overline{\gamma}_c e^{-\eta l_p}}\right). \tag{35}$$

The overall miss probability of single-carrier DS-CDMA is given by (27) with $P_{D_{l_p}}$ given by (33), (34), or (35), and with L_p in (27) replaced by L_1. The false alarm probability of the single-carrier DS-CDMA benchmarker scheme can be derived from (29) or (32) by setting $U = 1$, yielding

$$P_{FA} = \exp\left(-\frac{h}{2}\right). \tag{36}$$

Finally, the mean acquisition time of the serial search mode for the single-carrier DS-CDMA benchmarker can be evaluated by substituting (27) associated with (33), and (36) as well as the other related parameters into (4).

Note that, for the same system bandwidth and the same transmitted energy per chip, since the bandwidth of the single-carrier DS-CDMA signal is a factor of U higher, than that of the subcarrier signals in the MC DS-CDMA system using U subcarriers, the PN sequence chip duration of the single-carrier DS-CDMA signals, T_{c1}, is a factor of U lower, than that of the MC DS-CDMA signals, i.e., $T_{c1} = T_c/U$. Hence, for a fading channel having a delay spread of $T_m > T_c$, the number of resolvable paths, L_1, of the single-carrier DS-CDMA signals is at least a factor of U higher, than the number of resolvable paths, L_p, of the MC DS-CDMA signals. However, for a constant integral dwell time τ_D, as shown in Fig. 2, the energy collected by the single-carrier DS-CDMA detector during the integral dwell time of τ_D is a factor of U higher, than that collected by the MC DS-CDMA correlators, since the number of chips within the integral dwell time of τ_D for the single-carrier DS-CDMA is a factor of$U$ higher, than that for MC DS-CDMA. Bearing these relationships between the MC and single-carrier DS-CDMA systems in mind, let us now estimate and compare the code acquisition performance of the MC and single-carrier DS-CDMA systems.

VI. Numerical Results

In this section, the code acquisition performance of the single-carrier and MC DS-CDMA systems were evaluated and compared in conjunction with EGC and SC. The performance comparison between the single-carrier DS-CDMA system and the MC DS-CDMA systems using different number of subcarriers is based on the assumptions that these systems support the same data rate and use the same total transmitted energy. In other words, the same data block is transmitted by the above CDMA systems within the same time duration using the same amount of energy. As an application for the serial search considered, we used a PN sequence of length 1023. Consequently, q, which determined the length of the uncertainty region, was 2046, since the search step size was assumed to be half of the chip duration. We have assumed that the integral dwell time, τ_D, was the same for both the single-carrier and MC DS-CDMA systems, hence, it is convenient for us to consider the normalized mean acquisition time, which was derived from (4) divided by τ_D. All results were evaluated from (4), (25), (27), and (29) for EGC and from (4), (25), (30), and (32) for SC, while from (4), (25), (34), and (36) for single-carrier DS-CDMA. Note that, the system parameters were shown at the top of each figure.

Fig. 3 shows the influence of the fading parameter m and the number of subcarriers U on the overall miss probability for both the EGC [Fig. 3(a)] and the SC [Fig. 3(b)] schemes, where the values of $m = 1, 2$, and 50 represent Rayleigh fading, Rician fading and near-AWGN channels, respectively. From the results, we observe that for both the EGC scheme of Fig. 3(a) and for the SC arrangement of Fig. 3(b) assuming a sufficiently high signal-to-noise ratio (SNR)/chip value, the overall miss probability decreases, when m or U increases. However, the reduction of the overall miss probability for the EGC scheme due to increasing U is more significant, than that for the SC scheme. As seen in Fig. 3(b), it is difficult to distinguish the curves for $U = 1, 2, 4$, when the SNR/chip is lower than -8 dB. By contrast, for the EGC scheme of Fig. 3(a), we can obtain at least 2-dB gain over the whole range considered, when U is increased from one to two, or from two to four, respectively.

In Fig. 4, we evaluated and compared the overall miss probability versus the threshold performance of both the single-carrier and MC DS-CDMA systems for the Rayleigh fading, Rician fading and near-AWGN channels. As expected, the overall miss probability of both EGC and SC increases for a given value of U and for a given value of m, as the threshold, h, increases. In addition to our observations in Fig. 3 with

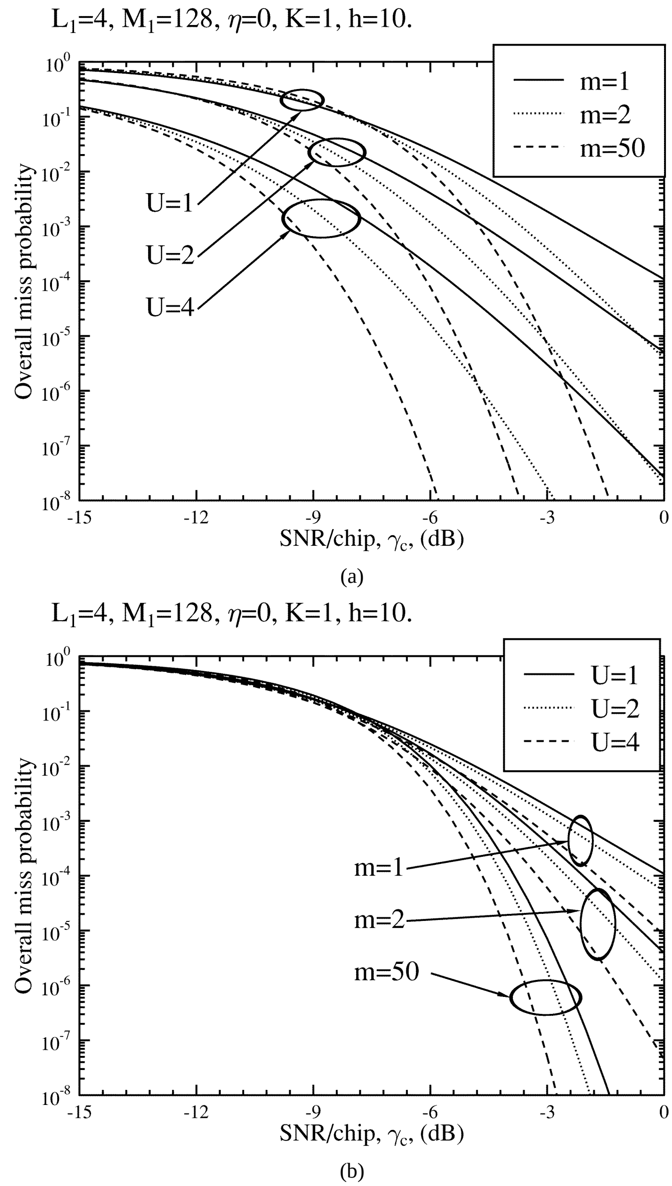


Fig. 3. Overall miss probability versus the SNR per chip, γ_c, performance for the single-carrier serial search acquisition ($U = 1$) and for the MC ($U = 2, 4$) DS-CDMA schemes over multipath Nakagami-m fading channels using $m = 1, 2,$ and 50..

respect to U and m, in Fig. 4 there exists a crossover point for the curves associated with $m = 1, 2$, and 50 for any given value of U. It can be shown that for the threshold values to the left of the crossover point, the overall miss probability decreases, when the channel fading becomes less severe, i.e., when increasing the value of m. However, for threshold values to the right of the crossover point, the overall miss probability increases, when the channel fading becomes less severe. From the results we notice furthermore that, for the EGC scheme, the crossover point moves to the right, when increasing the number of subcarriers combined, while for the SC scheme the crossover point changes insignificantly, when changing the number of subcarriers combined.

Fig. 5 shows the mean acquisition time performance versus the threshold h and the SNR/chip for the EGC scheme [Fig. 5(a)] and for the SC scheme [Fig. 5(b)], respectively.

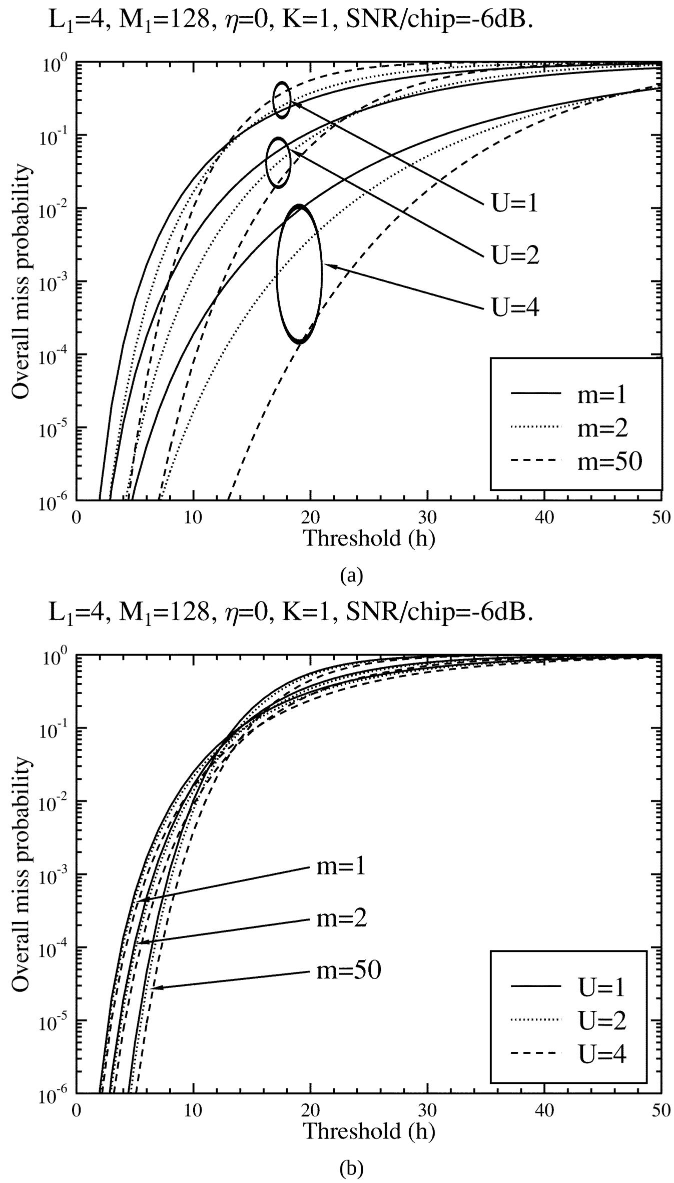


Fig. 4. Overall miss probability versus the threshold, h, performance for the single-carrier serial search acquisition ($U = 1$) and for the MC ($U = 2, 4$) DS-CDMA schemes over multipath Nakagami-m fading channels using $m = 1, 2,$ and 50.

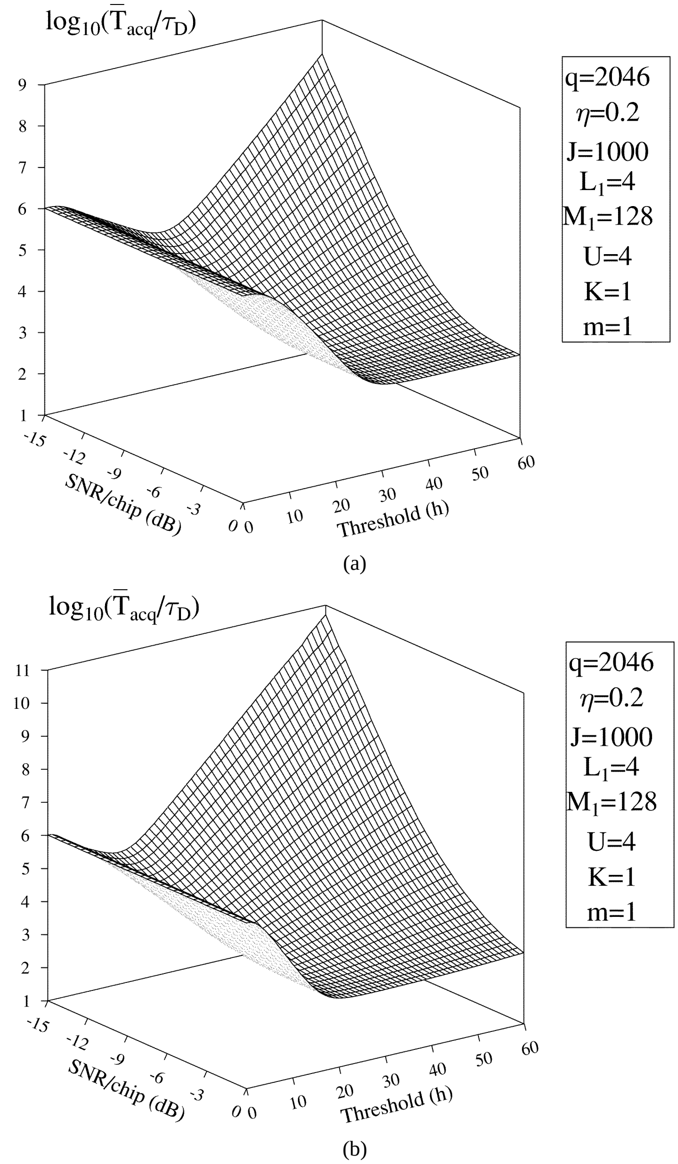


Fig. 5. Mean acquisition time versus the SNR per chip, γ_c, and versus the threshold, h, performance for the serial search acquisition of MC ($U = 4$) DS-CDMA over multipath Rayleigh ($m = 1$) fading channels.

It is clear from Fig. 5(a) and Fig. 5(b) that an inappropriate choice of the detection threshold h can lead to severe increase of the mean acquisition time, but the sensitivity of the mean acquisition time to the threshold decreases, as the SNR/chip increases. For any given SNR/chip value there exists an optimal choice of the threshold h, which minimizes the mean acquisition time. In addition, for any given threshold h, the mean acquisition time decreases, as the SNR/chip increases, and finally can reach a residual value, which is essentially due to the "penalty time" associated with switching back to the search mode after a false alarm. This value can be computed from (4) by setting $P_M(\lambda) = 0$, resulting in $\overline{T}_{\rm acq} \approx (1 + JP_{FA})/(2) \cdot (q\tau_D)$.

Fig. 6 presents the mean acquisition time performance of the EGC [Fig. 6(a)] and SC [Fig. 6(b)] schemes against the threshold h. For any given number of subcarriers combined and for a given value of m, there is an optimal choice of the threshold h, which leads to the minimum mean acquisition time. At the optimal value of h, we notice that for the EGC scheme using $U = 1$ the mean acquisition time performance is degraded, when increasing the value of m, while for the EGC scheme using $U = 2, 4$ and the optimum threshold, the mean acquisition time performance is slightly improved, when increasing the value of m. However, for the SC scheme and for any given U, the mean acquisition time performance at the optimal value of h is degraded slightly, when increasing the value of m. Furthermore, if the value of the threshold is set inappropriately, the mean acquisition time will significantly increase, which is further aggravated upon increasing the value of m for h-values in excess of the optimum. Taking the EGC scheme of Fig. 6(a) as an example, this observation can be explained with the aid of (4), (29), and Fig. 4(a) as follows. According to (29), the false alarm probability is a constant for a given value of h and for a given

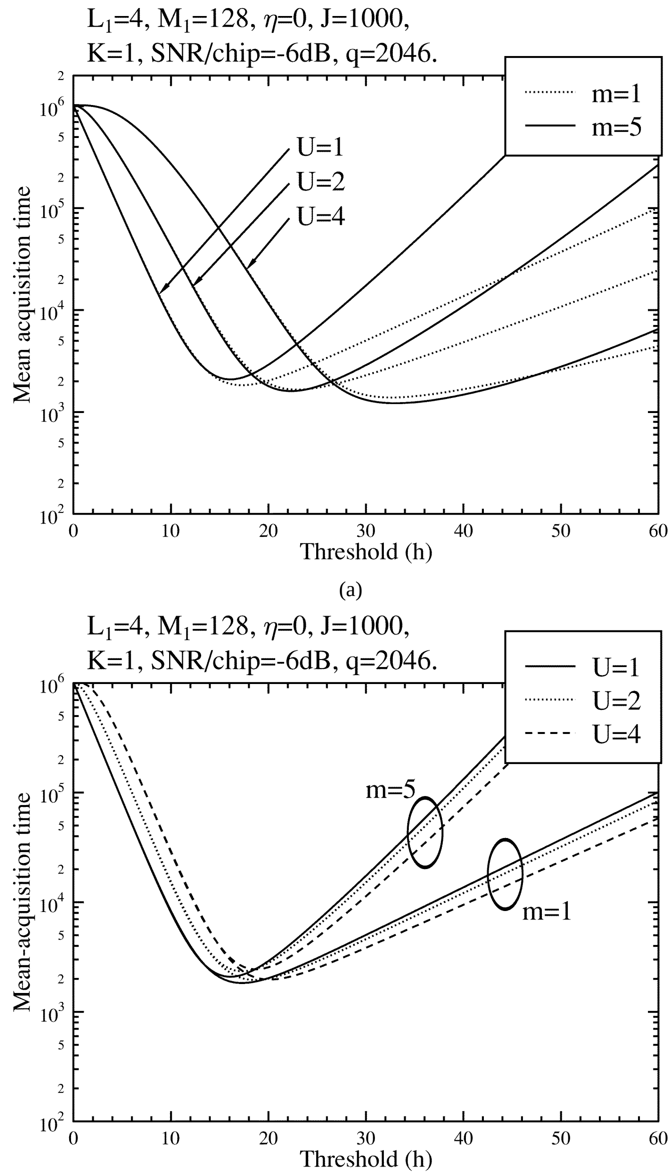


Fig. 6. Mean acquisition time versus the threshold, h, performance for the single-carrier serial search acquisition $(U = 1)$ and for the MC $(U = 2, 4)$ DS-CDMA schemes over multipath Nakagami-m fading channels using $m = 1, 5$.

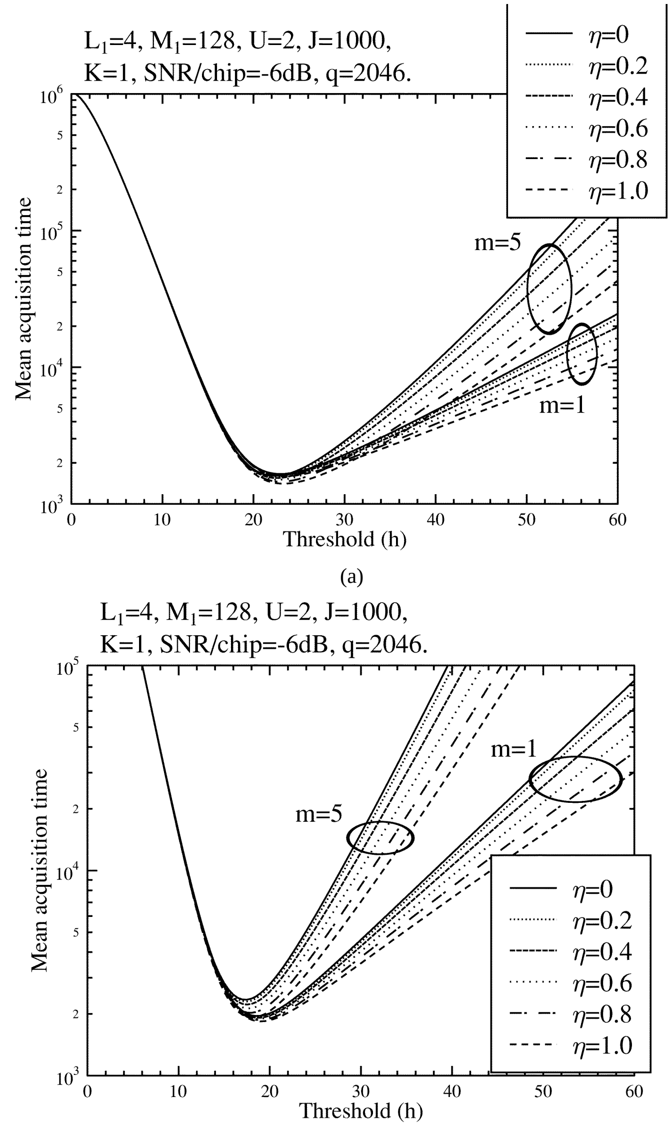
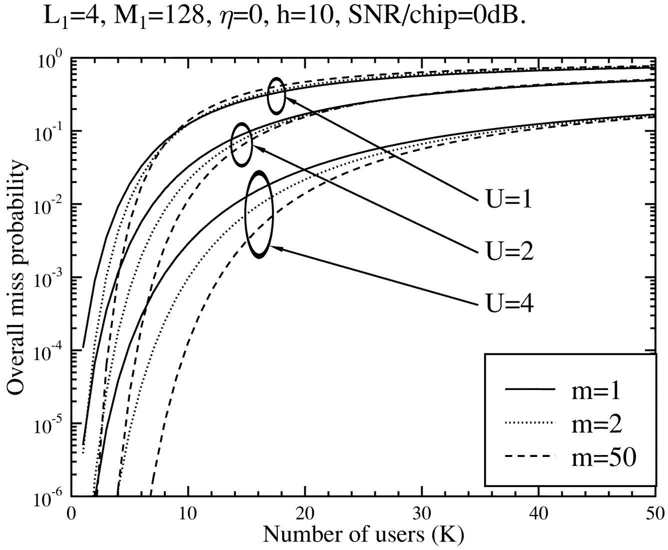
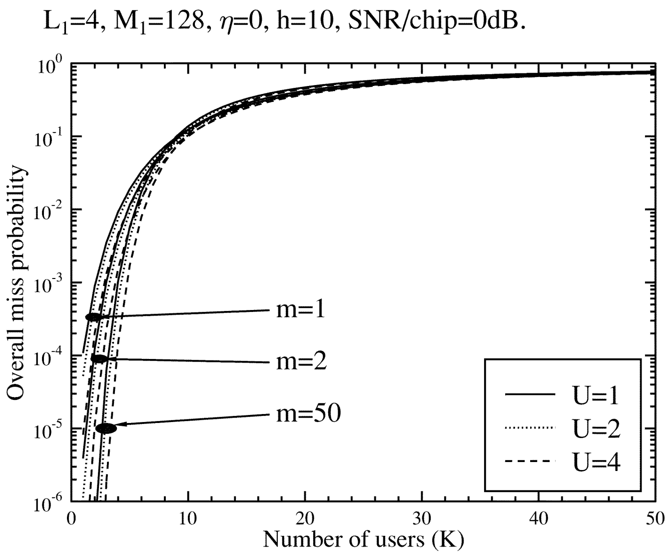


Fig. 7. Mean acquisition time versus the threshold, h, performance for the serial search acquisition MC $(U = 2)$ DS-CDMA schemes over multipath Nakagami-m fading channels using $m = 1, 5$ and the MIP decaying parameters of $\eta = 0, 0.2, 0.4, 0.6, 0.8, 1$.

value of U. Moreover, for the given values of J, P_{FA}, q, and τ_D, it can be shown from (4) that the mean acquisition time depends only on the overall miss probability, $P_M(\lambda)$. The mean acquisition time increases, as the overall miss probability increases. According to Fig. 4(a), for any given value of U, there exists a crossover point, above which the overall miss probability increases, when increasing the value of m, and below which the overall miss probability decreases upon increasing m, respectively. Consequently, for a given value of U, if the threshold is set lower than the crossover point, the mean acquisition time will decrease, when the value of m increases. Conversely, if the threshold is set higher than the crossover point, the mean acquisition time will increase, when the value of m increases. Furthermore, according to Fig. 4(a), since the crossover point occurred at around the overall miss probability of 10^{-1} and since in (4) the overall miss probability appears in the form of $(1+P_M(\lambda))$ and $(1 - P_M(\lambda))$, the reduction of $P_M(\lambda)$ due to increasing m has little influence on these terms. Hence, the improvement of the mean acquisition time performance due to increasing m is insignificant, as shown in Fig. 6(a). However, threshold values higher than the crossover point may have significant influence on the terms of $(1 + P_M(\lambda))$ and $(1 - P_M(\lambda))$, since in this range the overall miss probability is higher than 10^{-1}. Consequently, in this h-range, we observe that the mean acquisition time increases significantly, when increasing the value of m. However, as we noticed in the context of Fig. 6(a), the mean acquisition time performance of the EGC scheme is improved significantly and becomes more robust to the threshold for values in excess of the optimum, when more subcarrier signals are combined. However, in contrast to the EGC scheme, for the SC scheme the improvement of the mean acquisition time



(a)



(b)

Fig. 8. Overall miss probability versus the number of active users, K, performance for the single-carrier serial search acquisition ($U = 1$) and for the MC ($U = 2, 4$) DS-CDMA schemes over multipath Nakagami-m fading channels using $m = 1, 2, 50$.

performance due to the increasing of the number of subcarriers is much less significant.

The effect of the average power decay rate, η, of the multipath CIR on the mean acquisition time performance for both the EGC and SC schemes is shown in Fig. 7. As shown in Fig. 7(a) and Fig. 7(b), the mean acquisition time performance is improved, as η increases from zero to one, implying a more rapidly decaying MIP.

Finally, in Fig. 8, we evaluated and compared the overall miss probability versus the number of active users performance of both the single-carrier and MC DS-CDMA systems for the Rayleigh fading ($m = 1$), Rician fading ($m = 2$), and near-AWGN ($m = 50$) channels. As expected, the overall miss probability of single-carrier DS-CDMA and that of MC DS-CDMA using both the EGC [Fig. 8(a)] and SC [Fig. 8(b)] schemes increases, when the number of active users increases. Again, as shown in Fig. 3 for MC DS-CDMA using the EGC scheme, which is characterized in Fig. 8(a), the overall miss probability decreases significantly upon increasing the number of subcarrier signals combined. However, for MC DS-CDMA using the SC scheme, which is characterized in Fig. 8(b), the improvement due to increasing U is much less significant, than that for the EGC scheme.

VII. Conclusion

In summary, in this contribution the code acquisition performance of single-carrier and MC DS-CDMA systems has been investigated and compared with various Nakagami-m fading channels under the hypothesis of multiple synchronous states (H_1 cells) in the uncertainty region of the PN code. The acquisition performance of the MC DS-CDMA system was evaluated, when the correlator outputs of the subcarriers associated with the same phase of the local PN code replica were noncoherently combined using both EGC and SC schemes. We have studied the effects of the threshold, the SNR per chip, that of the fading parameter m, the number of subcarriers, the average power decay rate as well as that of the multiuser interference on the code acquisition performance of single-carrier DS-CDMA and that of MC DS-CDMA systems associated with EGC and SC. From the results we conclude that, if the detection threshold is set inappropriately, the code acquisition performance might be degraded significantly, as the channel quality quantified in terms of m becomes better. In Nakagami-m fading channels, the code acquisition performance of a MC DS-CDMA system using EGC improves significantly, as the number of subcarrier signals combined increases. By contrast, the code acquisition performance of the equivalent MC DS-CDMA system using SC improves only insignificantly and becomes similar to that of the corresponding single-carrier DS-CDMA system, when increasing the number of subcarriers. Furthermore, the code acquisition performance of a MC DS-CDMA system using EGC is better than that of a MC DS-CDMA system using SC. It was found that the code acquisition performance of a MC DS-CDMA system using EGC becomes more robust to the detection threshold, as the number of subcarriers increases.

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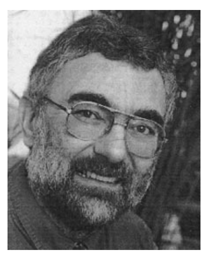

Lajos Hanzo (M'91–SM'92) received the master degree in electronics in 1976 and the doctorate in 1983.

During his 26-year career in telecommunications, he has held various research and academic posts in Hungary, Germany, and the U.K. Since 1986, he has been with the Department of Electronics and Computer Science, University of Southampton, Southampton, U.K., where he holds the Chair in telecommunications. He has co-authored eight books on mobile-radio communications, published about 400 research papers, organized and chaired conference sessions, presented overview lectures, and has been awarded a number of distinctions. Currently, he is managing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) U.K., the European IST Programme, and the Mobile Virtual Center of Excellence (VCE), U.K. He is an enthusiastic supporter of industrial and academic liaison and he offers a range of industrial courses.

Dr. Hanzo is an IEEE Distinguished Lecturer.