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Detection Performance of MC-CDMA Parallel Acquisition with Reference Filter in a Multipath Fading Channel

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요 약

본 논문에서는 잡음 예측 필터를 적용한 멀티 캐리어 CDMA 병렬 동기 시스템을 위한 임계치의 통계적인 해석에 중점을 둔다. 시스템 성능 척도로써 평균 동기 획득 시간을 검파 확률과 오보 확률의 관점에서 유도한다. 다중경로 페이딩 채널에서 평균 동기 획득 시간을 유도한다. 수치해석 결과, 잡음 예측 필터를 적용한 멀티 캐리어 CDMA 병렬 동기 해석에 있어서 임계치의 통계적인 특성을 이용한 동기 해석이 임계치의 근사화에 의한 동기 해석보다 정확한 결과를 보임을 알 수 있다. 또한, 잡음 예측 필터를 적용한 멀티 캐리어 CDMA 병렬 동기 시스템이 넓은 범위의 SNR에 대해서 평균 동기 획득 시간을 최소화할 수 있는 임계치를 검파할 수 있음을 확인할 수 있다.

Ⅰ. Introduction

In recent years, there has been increasing interest in using direct-sequence spread-spectrum (DS-SS) code division multiple access (CDMA) for various applications. DS-CDMA is described for cellular, indoor, and satellite communications [1, 2]. Generally, the performance of DS-CDMA degrades rapidly when the number of users increase and in high data rate application DS-SS may be subject to severe inter-symbol-interference (ISI). Multicarrier CDMA systems of various types have been proposed for high data rate applications to reduce the effect of ISI [3]. In [4], MC-CDMA systems were proposed to solve the interchip-interference (ICI) problem by transmitting the same data symbol over a large number of narrow orthogonal carriers. MC-DS-CDMA system introduced in [5] ulilizes a small number of carriers to solve both the ISI and ICI problems.

A wide variety of code acquisition methods have been proposed, analyzed and applied in a wide range of applications. Acquisition algorithms for DS-SS system employing matched filters (MFs) are considered [6, 7, 8]. An approach using a bank of N parallel I-Q noncoherent PN matched filters (PNMFs) is proposed in [6]. After suitable processing, the outputs of these matched filters are compared to adjustable thresholds to detect proper time alignment of the synchronizing PN sequences. The threshold adaptation algorithms are designed to achieve fast and reliable acquisition. In [7, 8], which uses baseband matched filter processing of the received PN code, the threshold for the alignment decision is provided by a reference matched filter. In these algorithms, the running average of the output of a reference MF is estimated to be $2\sigma_R^2$, where σ_R^2 is the variance of the

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output of each of the MF correlators. The result multiplied by a weighting factor, $2K\sigma_R^2$, is used as a decision threshold.

This paper presents a statistical analysis of the decision threshold of the acquisition of MC-CDMA system described in [5]. The acquisition scheme employs a reference filter to estimate the variance of interference at the output of the MF. To examine the performance of the parallel acquisition system with reference filtering, an expression for the mean acquisition time is derived in terms of the probabilities of detetion and false alarm. These parameters are analyzed for a multipath Rayleigh fading channel. It is shown that DS-MC-CDMA parallel acquisition system with reference filter gives better performance and is a good candidate for MC-CDMA system than other previous schemes [9] without reference filter. Also, it is shown that the statistical evaluation of the decision threshold seems more appropriate in the performance analysis of the acquisition system with a reference filter than the approximation of the decision threshold adopted in other schemes [7, 8].

The MC system and the acquisiton system are described in Section 2. Section 3 presents the channel model. In Section 4, the probabilities of detection and false alarm are derived and the mean acquisition time is evaluated as a measure of the system performance in multipath fading fading environments. Some numerical results are presented in Section 5. Finally, conclusions are discussed in Section 6.

Ⅱ. Acquisition System Description

The transmitter of the MC-CDMA system is described in [5]. At the transmitting side, the bit stream with symbol duration T_{s1} is serial-to-parallel converted into P parallel streams with a symbol duration $T_s = PT_{s1}$. Each stream feeds S parallel streams such that the same data stream exisists on the S branches. All data streams are spread by the same PN code $PN_k(t)$ of length N and chip duration T_c. The transmission bandwidth BW is assumed to be passband null-to-null BW $2/T_{c1}$, where T_{c1} is the PN code chip duration for the single carrier (SC) system and the orthogonal frequencies w_m are related by

$$w_m = w_1 + (m-1)\frac{2\pi}{T_c},\ m = 1, 2, \cdots, S. \tag{1}$$

To maintain the same BW as the SC system for any selection of P and S, the chip duration and the code length must follow

$$T_c = \frac{PS+1}{2} T_{c1} \text{ and } N = \frac{2P}{PS+1} N_1 \tag{2}$$

where N_1 is the period of the PN code for the SC system.

In evaluating the performance of the MC-CDMA parallel acquisition system with reference filter, we consider the acquisition system similar to [9]. The functional block diagram of the parallel PN code acquisition system with reference filter is shown in Fig. 1. The search mode, as shown in Fig. 1, consists of a bank of $P\cdot S$ parallel detecting I-Q passive noncoherent PN matched filters and a reference I-Q PN matched filter. The structure of I-Q matched filter is same to [9]. The number of taps on each delay line is M/Δ with ΔT_c delay between successive taps, where M is the MF length and Δ is a phase adjustment parameter. For our analysis, a typical value for Δ is 1/2. The full period of the PN code of N chips is divided into subcodes each having length $N/(P\cdot S)$. As a reference input, each of the $P\cdot S$ detecting I-Q PNMF has the first M chips of these subcodes, respectively, and the reference I-Q PNMF is loaded with a PN code orthogonal to the transmitted PN code [7].

In $NT_c/(P\cdot S)$ seconds, N/Δ samples are collected from the $P\cdot S$ parallel detecting MF's, the largest of the resulting N/Δ samples is chosen, and a running average of the output of a reference I-Q MF is multiplied by a weighting factor K_1. If the largest of N/Δ samples exceeds R_{K_1} which is the running average multiplied by K_1, the corresponding phase is assumed tentatively to be coarsely aligned with the received PN code signal, and the acquisition system goes to the verification mode; otherwise, no coarse alignment is achieved.

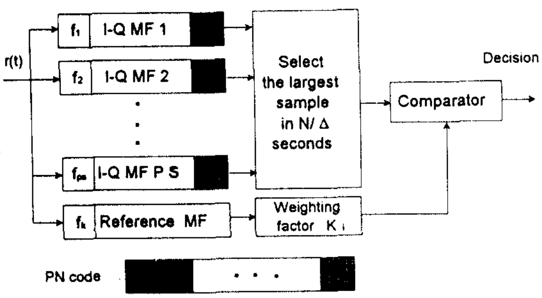

Fig. 1 Parallel acquisition system with reference filter

The verification mode employs a coincidence detector similar to [6, 7]. All MF's are loaded with the code phase selected by the search mode and the receiver runs with the same rate as the incoming PN code. In MT_c seconds, $A \le P \cdot S$ samples are taken in parallel. If at least B of A samples exceed R_{K_2} which is the running average multiplied by K_2, acquisition is declared and the tracking system is initiated, otherwise the acquisition process is reactivated after JMT_c penalty time.

Ⅲ. Statistical analysis of decision threshold

3.1 Multi-path fading channel

The considered multipath fading channel is modeled as consisting of a continuum of multipaths. Since a SS system can resolve multipath signals with delay $T_m > T_c$, this channel model results in a fixed number of resolvable Rayleigh faded paths. The low-pass impulse response of the channel for user k is given by

$$h_k(t) = \sum_{l=1}^{L} g_{k,l}\, \delta(t - t_{k,l}) \tag{3}$$

where $L = \lfloor T_m / T_c \rfloor + 1$ is the number of resolvable paths [10] and $t_{k,l} = (l-1)T_c + \zeta_{k,l}$ is the delay of the l-th path of the k-th user, assumed equal for all carriers of the same user. $g_{k,l} = \varphi_{k,l} \exp(j\gamma_{k,l})$ is assumed to be a Rayleigh random variable where $\varphi_{k,l}$ is the l-th path gain and $\gamma_{k,l}$ is the l-th path phase. $\zeta_{k,l}$ is uniformly distributed in $[0, T_c)$.

The channel auto-covariance function can be given by

$$\mu_k(t) = \sum_{l=1}^{L} \beta_l^2\, \delta(t - t_{k,l}) \tag{4}$$

with $\sum_{l=1}^{L} \beta_l^2 = 1$.

It is assumed that power control is applied such that without fading, all user signals would arrive at the intended receiver with equal power. Considering the interference caused by the other $Q-1$ users, the received signal takes the form

$$r(t) = \sum_{l=1}^{L} \sum_{k=1}^{Q} \sum_{m=1}^{PS} \sum_{i=-\infty}^{\infty} [\sqrt{2} x_i^{(m,l,k)} a_i^{(k)} \cos(w_m t + \phi_{i,l,k}) - \sqrt{2} y_i^{(m,l,k)} a_i^{(k)} \sin(w_m t + \phi_{i,l,k})] + n(t), \quad iT_c \le t \le (i+1)T_c \tag{5}$$

where $a^{(k)}(t) = \sum_{j=-\infty}^{\infty} a_j^{(k)} p(t - jT_c)$, $a_j^{(k)} = \pm 1$ being the PN code of the k-th user, the sets $\{\phi_{i,j,k}\}$ are i.i.d. uniformly distributed random variables that takes values in $[0, 2\pi)$, and $n(t)$ represents AWGN with double-sided power spectral density $N_0/2$ and zero mean. $p(t)$ is a real function of time, assumed a square pulse from 0 to T_c seconds that take a value of 1.

3.2 Statistics of decision threshold

In our analysis we consider a Rayleigh fading channel in [6], where the fading process is regarded as a constant over successive chips and these successive groups of chips are correlated. Under hypothesis $H_i : i = 0, 1$, e_I and e_Q follow the zero-mean gaussian distribution with variances $\sigma_0^2 = MT_c^2 \sigma_s^2 + \sigma_n^2$ and $\sigma_1^2 = WT_c^2 \sigma_s^2 + \sigma_n^2$, respectively. Under hypothesis H_1, W is given by

$$W = M + 2\sum_{j=1}^{M-1} (M-j)\,\rho(jT_c) \tag{6}$$

where $\rho(t)$ is the correlation coefficent. Referring to [6], the pdf of $R_k = e_I^2 + e_Q^2$ under hypothesis H_0 and H_1 follows the χ^2 distribution with two degrees of freedom:

$$f_R(y|H_i) = \frac{1}{2\sigma_i^2}\exp\left(-\frac{y}{2\sigma_i^2}\right),\ i=0,\ 1. \tag{7}$$

Referring to Fig. 1, the decision thresholds of the search and verification modes, R_{K_i}, are expressed as

$$R_{K_i} = \frac{K_i}{2M}\sum_{k=1}^{2M} R_k,\ i=1,\ 2. \tag{8}$$

In [7, 8], the decision threshold for the code acquisition defined as (8) is approximated as $2K_i\sigma_K^2$. It can be readily shown that under the assumption which the reference code and the transmitted code are purely orthogonal, the variance of the output of each of the MF correlators in the reference MF is given by $\sigma_K^2 = \sigma_0^2$ [7]. From this assumption, the pdf of R_k in (8) follows the central χ^2 distribution with two degrees of freedom defined in (7).

Therefore, the pdf of R_{K_i} follows the χ^2 distribution with $2M$ degrees of freedom [10]

$$f_{R_{K_i}}(y) = \frac{M^{2M}}{(K_i\sigma_0^2)^{2M}\Gamma(2M)}\, y^{2M-1}\exp\left(-\frac{My}{K_i\sigma_0^2}\right),$$
$$i=1,\ 2. \tag{9}$$

For the output of user one's MF of carrier q and n-th path, the interference analysis can be divided into two parts [5]: 1) the interference only caused by the paths of the same carrier and 2) the interference caused by different carriers and different pahts. Since all the samples are collected and compared as shown in Fig. 1, we can assume the first to be the strongest path without losing generality, which causes the real H_1 cell. In the considered multipath fading channel with L paths, there is one H_1 cell, $(L-1)$ $H_{0,\ n}$ cells, and $(2N-L)$ H_0 cells where $H_{0,\ n}$ are matched cells caused by the other $(L-1)$ paths but are not denoting the correct phase. For hypothesis H_1 and $H_{0,\ n}$, the matching path can be treated the same way as the H_1 cell in one-path Rayleigh fading. The output of the in-phase branch can be given by [9]

$$\sigma_{1,\ n}^2 = WT_c^2\sigma_s^2\beta_n^2 + \sigma_n^2 + \sum_{i=1}^{M}\sum_{\substack{l=1\\ l\neq n}}^{L}\Bigg[\frac{\sigma_s^2T_c^2}{6}\sum_{k=1}^{Q}\sum_{\substack{v=1\\ k=1,\ v\neq n}}^{L}$$
$$\left(\beta_v^2C_1^{(k)} + \frac{3}{\pi^2}\beta_v^2C_2^{(k)}\sum_{\substack{m=1\\ m\neq q}}^{PS}\frac{1}{(m-q)^2}\right)\Bigg] \tag{10}$$

where $C_1^{(k)} = 4 + a_{i-v+n}^{(k)}(a_{i-v+n+1}^{(k)} + a_{i-v+n-1}^{(k)})$ and $C_2^{(k)} = (a_{i-v+n+1}^{(k)} - a_{i-v+n-1}^{(k)})^2$. Under hypothesis H_0 the variance can be written as

$$\sigma_0^2 = QMT_c^2\sigma_s^2 + \sigma_n^2 + \frac{QMT_c^2\sigma_s^2}{\pi^2}\sum_{\substack{m=1\\ m\neq q}}^{PS}\frac{1}{(m-q)^2}. \tag{11}$$

Ⅳ. Noncoherent Detector Analysis

In our analysis, we assume uniform multipath power profile ($\beta_l^2 = 1/L$). In deriving the probability expressions, the same assumptions used in [6] are adopted. The detection probability of the search mode is the probability that the H_1 cell exceeds all the $(2N-L)$ H_0 cells, $(L-1)$ $H_{0,\ n}$ cells and threshold R_{K_1}, which is given by

$$P_{DS} = \int_0^{\infty}\frac{1}{2F_1}\exp\left(-\frac{y}{2F_1}\right)\left[1-\exp\left(-\frac{y}{2F_0}\right)\right]^{2N-L}$$
$$\prod_{n=2}^{L}\left[1-\exp\left(-\frac{y}{2F_n}\right)\right] \tag{12}$$
$$\cdot\left[1-\exp\left(-\frac{My}{K_1F_0}\right)\sum_{k=0}^{2M-1}\frac{1}{k!}\left(\frac{My}{K_1F_0}\right)^k\right]dy.$$

If we denote SNR/chip as $\Gamma = 2T_c\sigma_s^2/N_0L$, then

$$F_n = \frac{W}{M}\Gamma + 1 + \frac{\Gamma}{M}\sum_{i=1}^{M}\sum_{\substack{l=1\\ l\neq n}}^{L}\Bigg[\frac{1}{6}\sum_{k=1}^{Q}\sum_{\substack{v=1\\ k=1,\ v\neq n}}^{L}$$
$$\left(C_1^{(k)} + \frac{3}{\pi^2}C_2^{(k)}\sum_{\substack{m=1\\ m\neq q}}^{PS}\frac{1}{(m-q)^2}\right)\Bigg] \tag{13}$$

and

$$F_0 = QL\Gamma + 1 + \frac{QL\Gamma}{\pi^2} \sum_{\substack{m=1 \\ m \neq q}}^{PS} \frac{1}{(m-q)^2}. \tag{14}$$

The $(L-1)$ product term of (12) may be expressed in the form

$$\prod_{n=2}^{L}\left[1-\exp\left(-\frac{y}{2F_n}\right)\right] = 1 + \sum_{k=1}^{L-1}(-1)^k \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \prod_{j=1}^{k} \exp\left(-\frac{y}{2F_{i_j}}\right) = 1 + \sum_{k=1}^{L-1}(-1)^k \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \exp\left(-\frac{y}{2F_{sk}}\right) \tag{15}$$

where $i_1 < i_2 < \cdots < i_k$ and $F_{sk}^{-1} = \sum_{j=1}^{k} F_{i_j}^{-1}$. Substituting (15) into (12) and integrating, P_{DS} can be divided into four terms

$$P_{DS} = \sum_{n=0}^{2N-L}(-1)^n \binom{2N-L}{n} \Big[\frac{F_0}{F_0 + nF_1} - \frac{K_1}{2M} \sum_{k=0}^{2M-1} \left(\frac{2MF_1}{K_1F_0 + nKF_1 + 2MF_1}\right)^{k+1} + \sum_{k=1}^{L-1}(-1)^k \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \frac{F_0F_{sk}}{F_0F_{sk} + nF_1F_{sk} + F_0F_1} - \frac{K_1}{2M} \sum_{k=1}^{L-1}(-1)^k \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \sum_{l=0}^{2M-1} \left(\frac{2MF_1F_{sk}}{K_1F_0F_{sk} + K_1F_0F_1 + nK_1F_1F_{sk} + 2MF_1F_{sk}}\right)^{l+1} \Big]. \tag{16}$$

The missing probability of the search mode is the probability that all samples are less than R_{K_1}, which is given by

$$P_{MS} = \int_0^{\infty} \frac{M^{2M}}{(K_1F_0)^{2M}\Gamma(2M)} y^{2M-1} \exp\left(-\frac{My}{K_1F_0}\right) \left[1-\exp\left(-\frac{y}{2F_0}\right)\right]^{2N-L} \cdot \prod_{n=2}^{L}\left[1-\exp\left(-\frac{y}{2F_n}\right)\right]\left[1-\exp\left(-\frac{y}{2F_1}\right)\right] dy. \tag{17}$$

Similarly, substituting (15) into (17) and integrating, P_{MS} can be divided into four terms

$$P_{MS} = \sum_{n=0}^{2N-L}(-1)^n \binom{2N-L}{n} \Big[\left(\frac{2M}{nK_1 + 2M}\right)^{2M} - \left(\frac{2MF_1}{nK_1F_1 + 2MF_1 + KF_0}\right)^{2M} + \sum_{k=1}^{L-1}(-1)^k \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \left(\frac{2MF_{sk}}{nK_1F_{sk} + 2MF_{sk} + K_1F_0}\right) - \sum_{k=1}^{L-1}(-1)^k \cdot \sum_{i_1=2}^{L} \cdots \sum_{i_k=2}^{L} \left(\frac{2MF_1F_{sk}}{K_1F_0F_{sk} + K_1F_0F_1 + nK_1F_1F_{sk} + 2MF_1F_{sk}}\right)^{l+1} \Big]. \tag{18}$$

The false alarm probability of the search mode can be given by $P_{FS} = 1 - P_{DS} - P_{MS}$.

In a coincidence detection (CD), the probability of a successful CD at each test is the probability that an H_1 cell exceeds R_{K_2}, which is given by

$$P_C = 1 - \frac{K_2F_0}{2MF_1} \sum_{k=0}^{2M-1} \left(\frac{2MF_1}{K_2F_0 + 2MF_1}\right)^{k+1}. \tag{19}$$

For $N/\Delta \gg L$, the probability of a successful CD is given by

$$P_{CD} = \sum_{n=B}^{A} \binom{A}{n} P_C^n (1-P_C)^{A-n}. \tag{20}$$

When a false acquisition decision occurs, the probability of a false CD at each test is the probability that H_0 cells exceed R_{K_2}, which is gfiven by

$$P_{FC} = 1 - \frac{K_2}{2M} \sum_{k=0}^{2M-1} \left(\frac{2M}{K_2 + 2M}\right)^{k+1}. \tag{21}$$

Then the probability of a false CD is given by

$$P_{FCD} = \sum_{n=B}^{A} \binom{A}{n} P_{FC}^n (1-P_{FC})^{A-n}. \tag{22}$$

For the considered acquisition scheme with a parallel search, the mean acqusition time $E[T_{acq}]$ can be modified as [6]

$$E[T_{acq}] = \left\{ \frac{N(P \cdot S)^{-1} + M(1-P_{MS}) + JMP_F}{P_D} \right\} T_c \tag{23}$$

where $P_D = P_{DS} \cdot P_{CD}$ and $P_F = P_{FS} \cdot P_{FCD}$ denote the overall detection and false alarm probabilities, respectively.

V. Detection Performance Results

As an application for the MC-CDMA parallel acquisition system, we used the following parameters, namely: 1) a PN code with rate 10M chip/sec and length $N=1023$ is considered, 2) matched filter lengths (M) of 64 and 128 chips are taken, while the number of carriers is chosen $P \cdot S = 2 \cdot 4$, 3) $A=4$ and $B=2$, 4) the correlation coefficient $\rho(t)$ for the fading processis taken as ρ_1^{t/T_c} [6], and 5) $J=1000$ chips. For simplicity, the same weighting factors for the search and verifiaction modes is used, i.e., $K_1 = K_2 = K$.

The comparision between the approximation of the decision threshold adopted in [7, 8] and the statistical analysis of the decision threshold is given for the multipath fading channel in terms of the mean acquisition time performance. Tables I shows the mean acquisition time versus SNR/chip for various values of ρ_1 and $M=128$. The value of a weighting factor K_i is chosen to ensure the false alarm probability of the verification mode $P_{FCD} \leq 2 \times 10^{-3}$ for each value of SNR/chip. From Table I, it is observed that the approximation of the decision threshold is reasonable for SNR/chip〉−15dB and is considerably different from the exact evaluation for SNR/chip 〈−15dB.

Fig. 2 shows the mean acquisition time of the MC parallel acquisition in proposed in [9] and the MC parallel acquisition with reference filter in a multipath fading channel. For the acquisiton system without refernce filter, the threshold value is selected numerically to minimize the mean acquisition time for each value of SNR/chip. In the considered multipath fading channel, MC parallel acquisition system with reference filtering provides the desision threshold to give a sub-optimal mean acquisition time performance about the threoretical optimum mean acquisition time of the MC parallel acquisition system without reference filtering. Also, it is shown that for $K=4$, the mean acquisition time of the acquisition system with reference is approximately same the the optimum mean acquisition time of the acquisition system without a reference filter.

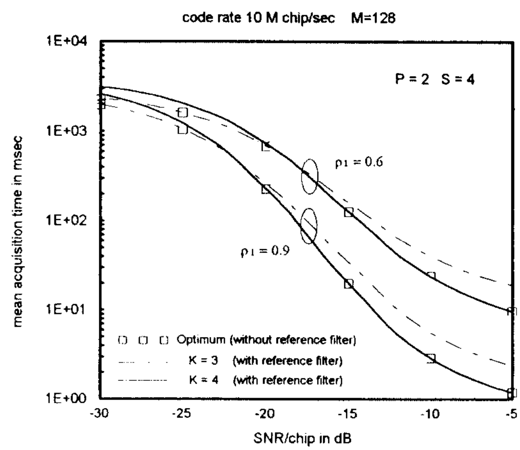

Fig. 2. Mean acqusition time for MC-CDMA parallel acquisition system (L = 4, Q = 4)

Table 1. Mean acquistion time versus SNR/chip for various values of ρ_1 and Q(L = 4)

SNR/chip	approximation (msec)				exace analysis (msec)			
	$\rho_1=0.6$		$\rho_1=0.9$		$\rho_1=0.6$		$\rho_1=0.9$	
	Q=4	Q=8	Q=4	Q=8	Q=4	Q=8	Q=4	Q=8
−10	23.97	23.10	2.56	5.20	24.05	23.20	2.89	5.65
−15	138.24	78.63	19.69	20.24	127.19	74.25	20.03	20.50
−20	862.87	448.96	254.29	170.03	727.60	390.16	228.08	155.24
−25	2562.44	1780.68	1497.58	1096.39	2055.08	1449.94	1234.16	914.98
−30	4004.89	3474.73	3303.99	2886.62	3138.41	2744.03	2614.63	2301.08

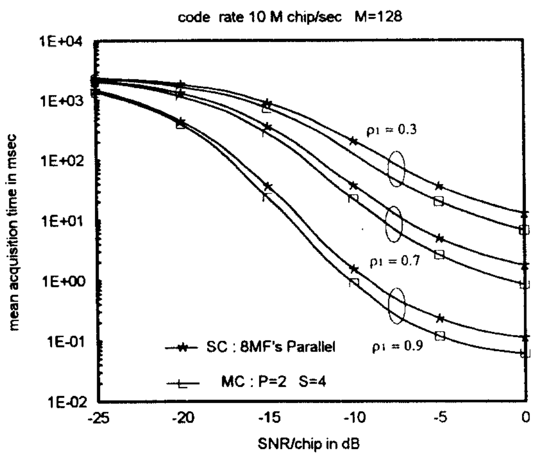

Fig. 3. Mean acquisition time for the SC and MC parallel acquisition systems (L = 4, Q = 4)

Fig. 3 presents the mean acquisition time performance for the various system and channel parameters. The weighting factor is selected numerically to minimize the mean acquisition time for each value of SNR/chip. A significant improvement of performance over the SC-CDMA system can be obtained by using the frequency diversity of the MC system. As expected, for faster fade rate (lower ρ_1), the mean acquisition time increases, i.e., the system is slower.

Ⅵ. Conclusions

This paper describes the statistical analysis of the decision threshold of multi-carrier CDMA parallel acquistion system with reference filtering in a multipath fading channel. MC-CDMA parallel acquisition system with reference filter has been compared with the conventional MS-CDMA parallel acquisition system in terms of the mean acquisition time performance. From the results, it is obserbed that: 1) With approximately the same degree of structuring complexity, the mean acquisition time of the MC-CDMA parallel system with reference filtering is comparable to the optimum mean acquisition time of the conventional MS-CDMA parallel system; 2) The statistical analysis of the desision threshold is more reasonable in the performance analysis of the parallel acquisition scheme withe reference filter than the approximation of the decision threshold adopted in other previous schemes [7, 8]; 3) Acquisition performance can be improved by making use of the frequency diversity of the MC system.

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