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Statistical Analysis of Decision Threshold for DS-SS Parallel Acquisition with Reference Filter in a Rician Fading Channel

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ABSTRACT

This paper presents a statistical analysis of the decision threshold for direct-sequence spread-spectrum (DS-SS) parallel Pseudo-Noise (PN) code acquisition with a reference filter. The probabilities of detection and false alarm are derived, and the mean acquisition time is evaluated as a measure of the system performance in both nonfading and Rician fading channels. From the statistical results, it is shown that in the performance analysis of the parallel acquisition system with reference filtering, the statistical evaluation of the decision threshold seems more appropriate than the approximation of the decision threshold adopted in other schemes[2, 3].

I. Introduction

The use of direct-sequence spread-spectrum(DS-SS) in mobile communications has been growing considerably over the past few years. In a line-of-sight environment, Rician fading is encounted. DS-SS is especially attractive in this situation due to its inherent anti-multipath capabilities [1]. Pseudo-Noise (PN) code acquisition is essential in any DS-SS system, where a synchronized replica of the transmitted PN code is required in the receiver to despread the received signal and allow the recovery of data sequence.

A wide variety of code acquisition methods have been proposed, analyzed and applied in a wide range of applications [2-9]. In the last few years, some parallel acquisition schemes were proposed in which a number of cells, less than the number of uncertainty region cells, are tested simultaneously [3-8]. In [6], a scheme that employs a bank of surface acoustic wave (SAW) convolvers is discussed. An approach using a bank of N parallel I-Q noncoherent PN matched filters (PNMFs) is proposed in [7, 8]. The threshold adaptation algorithms are designed to achieve fast and reliable acquisition [2, 3]. In [2], which uses baseband MF processing at the received PN sequence, the threshold for alignment decision is provided by a reference filter. Also, the parallel acquisition scheme with a reference filter is adopted to provide fast acquisition [3]. However, the running average of the output of a reference MF is approximated to be $2\sigma_R^2$, where $2\sigma_R^2$ is the variance of the output from each of the MF correlators. The result multiplied by a weighting factor, $2K\sigma_R^2$, is used as a decision threshold.

This paper is concerned with the statistical analysis of a decision threshold for the DS-SS parallel acquisition system with a reference filter described in [3]. The probabilities of detection and false alarm are derived for both nonfading and nonselective Rician fading channels. As a performance measure, the mean

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acquisition time is evaluated, and its insensitivity to the weighting factors K_1 and K_2 which are used to scale the sum of the output of the reference filter is highlighted. From the statistical analysis, 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 previous works [2, 3]. The performance of the proposed parallel acquisition system is compared to conventional parallel acquisition system, and it is shown that the mean acquisition time of the proposed parallel system is comparable to the optimum mean acquisition time of the conventional parallel system.

The parallel acquisition scheme with a reference filter is described in Section 2. In Section 3, the statistical analysis of the decision threshold is performed for both nonfading and non-selective Rician fading channels. Some numerical results are discussed in Section 4. Finally, concluding remarks are presented in Section 5.

Ⅱ. Parallel Acquisition System

The system under consideration has two modes of operation: the search mode and the verification mode. The search mode, shown in Fig. 1, consists of a bank of N parallel detecting I-Q passive noncoherent PNMF's and a reference I-Q PNMF, as described in [3]. The structure of I-Q PNMF is discussed in [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, Δ is a phase adjustment parameter, and T_c is the chip duration. For our analysis, a typical value for Δ is 1/2. Similar to [6, 7], the full period of the PN code of L chips is divided into N subsequences each of length $M = L/N$. As a reference input, each of the N detecting I-Q PNMF MF_D has one of the subsequence of length M and the reference I-Q PNMF MF_R is loaded with a PN code orthogonal to the transmitted PN code [2, 3].

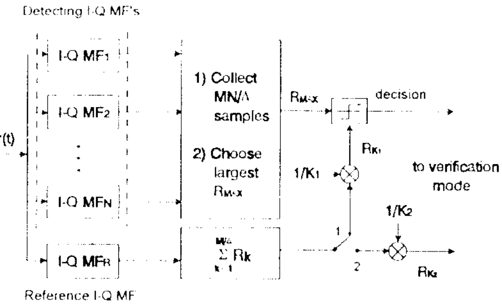

Fig. 1 Parallel acquisition system

After MT_c seconds, MN/Δ samples are collected from the N parallel detecting MF's and the largest of the resulting MN/Δ samples is chosen. The sum of M/Δ samples of the reference filter is divided by weighting factor K_1 (the switch is in position 1), where K_1 is an integer which constitutes a fundamental design parameter. If the largest of MN/Δ samples exceeds R_{K_1} which is the sum divided 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.

In the verification mode, a coincidence detection (CD) similar to [7, 8] is used to verify the selected phase by the search mode. When a phase is selected by the search mode (the switch is in position 2), it is loaded into the verification mode. The receiver advances this local phase by the same rate as the incoming PN code, and a sample is taken every MT_c seconds. If B out of A samples exceed R_{K_2} which is the sum divided by K_2, acquisition is declared and the receiver moves to the tracking system; otherwise the system goes back to the search mode. However, if false acquisition is declared, the phase handed to the tracking system will not be absorbed, and the acquisition process is reactivated after JMT_c penalty time.

Ⅲ. Statistical Analysis of Decision Threshold

This section provides the statistical analysis of the decision threshold for the parallel acquisition system with reference filtering. The probabilities of detection and false alarm are derived for both nonfading and nonselective Rician fading channels, and the mean acquisition time is evaluated.

3.1 Nonfading Channel

In deriving the probability expressions, the same assumptions used in [5-7] are adopted. The signal received by PNMF can be written as

$$r(t)=\sqrt{2S}\,c(t+\tau T_c)\cos(w_0 t+\theta)+n(t) \tag{1}$$

where S is the transmitter signal power, θ is uniformly distributed random phase, w_0 is the carrier frequency, $c(t+\tau T_c)$ is the code to be acquired, and $n(t)$ represents AWGN with double-sided power spectral density $N_0/2$ and zero mean. Let R_k denote the correlation value from the envelope detector. The probability density functions (PDFs) of $R_k=e_I^2+e_Q^2$ under H_1 and H_0 follow the noncentral and central χ^2 distributions, respectively[8]. These are given by

$$p_R(y|H_1)=\frac{1}{2\sigma_n^2}\exp\left(-\frac{m^2+y}{2\sigma_n^2}\right)I_0\left(m\frac{\sqrt{y}}{\sigma_n^2}\right) \tag{2}$$

and

$$p_R(y|H_0)=\frac{1}{2\sigma_n^2}\exp\left(-\frac{y}{2\sigma_n^2}\right) \tag{3}$$

where $\sigma_n^2=N_0MT_c/2$, $m^2=M^2T_c^2S$, and $I_0(x)$ is the modified Bessel function of first kind and zero order. Referring to Fig. 1, the decision thresholds of the search and verification modes can be expressed as, respectively

$$R_{K_i}=\frac{1}{K_i}\sum_{k=1}^{2M}R_k\,, \qquad i=1,\ 2 \tag{4}$$

Under the assumption that the reference code and the incoming code are purely orthogonal, the variance of the output of each of the MF correlators in MF_R can be denoted as $\sigma_R^2=\sigma_n^2$ [2]. From this assumption, the PDF of R_k in (4) follows (3) and the PDF of P_{K_i} defined as (4) follows the χ^2 distribution with $2M$ degrees of freedom. These PDFs are written as [10]

$$p_{R_{K_i}}(z)=\frac{K_i^{2M}}{(2\sigma_n^2)^{2M}\Gamma(2M)}z^{2M-1}\exp\left(-\frac{K_i z}{2\sigma_n^2}\right),\quad i=1,2 \tag{5}$$

where $\Gamma(p)=(p-1)!$.

The detection probability of the search mode P_{DS} is the probability that the H_1 cell is larger than all $2L-1$ cells and larger than decision threshold R_{K_1}. This probability can be defined as

$$\begin{aligned}P_{DS}&=\int_0^\infty p_R(y|H_1)\left[\int_0^y p_R(z|H_0)dz\right]^{2L-1}\int_0^y p_{R_{K_1}}(z)\,dzdy\\&=\int_0^\infty p_R(y|H_1)\left[1-\exp\left\{-\frac{y}{2\sigma_n^2}\right\}\right]^{2L-1}\\&\quad\cdot\left[1-\exp\left\{-\frac{K_1y}{2\sigma_n^2}\right\}\sum_{k=0}^{2M-1}\frac{1}{k!}\left\{\frac{K_1y}{2\sigma_n^2}\right\}^k\right]dy\end{aligned} \tag{6}$$

Substituting (2), (3), and (5) into (6), one can get

$$\begin{aligned}P_{DS}&=\sum_{n=0}^{2L-1}(-1)^n\binom{2L-1}{n}\left[\frac{1}{n+1}\exp\left\{-\frac{n}{n+1}M\gamma_c\right\}\right.\\&\quad-\frac{1}{K_1}\exp\left\{-\frac{n+K_1}{1+n+K_1}M\gamma_c\right\}\sum_{k=0}^{2M-1}\left(\frac{K_1}{1+n+K_1}\right)^{k+1}\\&\quad\left.\cdot F\left(-k,\ 1\ ;-\frac{M\gamma_c}{1+n+K_1}\right)\right]\end{aligned} \tag{7}$$

where $\gamma_c=ST_c/N_0$ is the SNR/chip and $F(a,\ b;c)$ is the confluent hypergeometric function. The missing probability of the search mode P_{MS} is the probability that all samples are less than R_{K_1}. This probability can be given by

$$\begin{aligned}P_{MS}&=\int_0^\infty p_{R_{K_1}}(y)\left[\int_0^y p_R(z|H_0)dz\right]^{2L-1}\int_0^y p_R(z|H_1)dzdy\\&=\int_0^\infty\frac{K_1^{2M}}{(2\sigma_n^2)^{2M}\Gamma(2M)}y^{2M-1}\exp\left\{-\frac{K_1y}{2\sigma_n^2}\right\}\\&\quad\cdot\left[1-\exp\left\{-\frac{y}{2\sigma_n^2}\right\}\right]^{2L-1}\left[1-Q\left(\frac{m}{\sigma_n},\frac{\sqrt{y}}{\sigma_n}\right)\right]dy\end{aligned} \tag{8}$$

where $Q(a,\ b)$ is the Marcum's Q function. Similarly, substituting (2), (3), and (5) into (8), and integrating, one gets

$$P_{MS} = \sum_{n=0}^{2L-1}(-1)^n\binom{2L-1}{n}\Bigg[\left(\frac{K_1}{n+K_1}\right)^{2M} - \left(\frac{K_1}{1+n+K_1}\right)^{2M} \cdot \exp\left\{-\frac{n+K_1}{1+n+K_1}M\gamma_c\right\}\sum_{k=0}^{\infty}\frac{(M\gamma_c)^k}{k!} \cdot F\left(k-2M+1,\ k+1\ ;\ -\frac{M\gamma_c}{1+n+K_1}\right)\Bigg] \tag{9}$$

The false alarm probability of the search mode can be obtained from P_{DS} and P_{MS} as $P_{FS} = 1 - P_{DS} - P_{MS}$.

In a coincidence detection, the probability of a successful CD at each test is given by

$$P_C = \int_0^{\infty} p_R(y|H_1)\int_0^{y} p_{R_{K_1}}(z)dzdy \tag{10}$$

When a false acquisition decision occurs, the probability of a false CD at each test is given by

$$P_{FC} = \int_0^{\infty} p_R(y|H_0)\int_0^{y} p_{R_{K_1}}(z)dzdy \tag{11}$$

Substituting (2), (3), and (5) into (10) and (11), we can easily get P_C:

$$P_C = 1 - \frac{1}{K_2}\exp\left\{-\frac{K_2}{1+K_2}M\gamma_c\right\}\sum_{k=0}^{2M-1}\left(\frac{K_2}{1+K_2}\right)^{k+1} \cdot F\left(-k,\ 1\ ;\ -\frac{M\gamma_c}{1+K_2}\right) \tag{12}$$

and P_{FC}:

$$P_{FC} = 1 - \frac{1}{K_2}\sum_{k=0}^{2M-1}\left(\frac{K_2}{1+K_2}\right)^{k+1} \tag{13}$$

The probabilities of a successful CD and a false CD are given by, respectively

$$P_{CD} = \sum_{n=B}^{A}\binom{A}{n} P_C{}^n(1-P_C)^{A-n}$$
$$P_{FCD} = \sum_{n=B}^{A}\binom{A}{n} P_{FC}{}^n(1-P_{FC})^{A-n} \tag{14}$$

Due to the Markovian nature of the acquisition process, the state transition diagram can be used in deriving the probability generating function of the acquisition time. For the considered acquisition scheme with a parallel search, the mean acquisition time $E[T_{acq}]$ is given by [8]

$$E[T_{acq}] = \frac{M + AM(1-P_{MS}) + JMP_F}{P_D}T_c \tag{15}$$

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.

3.2 Nonselective Rician Fading Channel

In our analysis we consider a nonselective Rician fading channel described in [7], where the bandwidth of both the direct path and the reflected diffused path is assumed wide enough to neglect the frequency selectivity, the fading process is regarded as a constant over k successive chips, $k \ll M$, and these successive groups of k chips are correlated. The received signal in a general Rician fading channel is given by

$$r(t) = Re\left\{\alpha\sum_{i=-\infty}^{\infty}\sqrt{2S}u_i(t-iT_c)e^{j(w_0 t+\theta)}\right\} + F(t) + n(t) \tag{16}$$

where $Re\{\cdot\}$ denotes the real part of $\cdot$, α is a real constant, w_0 is the carrier frequency, $u_i(t)$ is assumed a square pulse from 0 to T_c seconds that takes values of ± 1 according to the PN code, and $F(t)$ is the faded component at the output of the considered channel. In (16), the faded component $F(t)$ can be written as [7]

$$F(t) = \sum_{i=-\infty}^{\infty} Re\{\beta\sqrt{2S}x_{\lceil i/k\rceil}(t)\,u_i(t-iT_c)e^{jw_0 t}\} \tag{17}$$

where β is a real constant, $\lceil m/n \rceil$ = first integer $< m/n$, and $x_i(t)$ is a zero-mean complex Gaussian process with variances $E\{x_i(t)^2\} = \sigma_s^2$ and autocorrelations $E\{x_i(t)x_j^*(t)\} = \rho_{|i-j|}\ \sigma_s^2$, $i \neq j$. $1 \geq \rho_1 \geq \ldots \geq 0$ are autocorrelation coefficients among the fading processes and the smaller the correlation coefficients among the chips, the faster the fade rate. Referring to [7], the outputs of the I and Q branches of each I-Q PNMF are given by

$$e_I = S_I + F_I + N_I \quad \text{and} \quad e_Q = S_Q + F_Q + N_Q \tag{18}$$

where S_I and S_Q are outputs due to the specular component, and N_I and N_Q are independent identically distributed zero-mean Gaussian random variables with variance $\sigma_n^2 = N_0 M T_c/2$. Under hypothesis $H_i: i=0, 1$, F_I and F_Q follow the zero-mean Gaussian distribution with variances $\sigma_{F0}{}^2 = \beta^2 SMT_c^2\sigma_s^2$ and $\sigma_{F1}{}^2 = \beta^2 SWT_c^2\sigma_s^2$, respectively, where W is the conditional variance of a correct cell normalized by in-phase (or quadrature) signal variance as defined in [7]. The PDF of $R_k = e_I^2 + e_Q^2$ under H_1 and H_0 follows the noncentral and central χ^2 distributions, respectively. These can be given by

$$p_R(y|H_1) = \frac{1}{2(\sigma_{F1}^2+\sigma_n^2)}\exp\left(-\frac{m^2+y}{2(\sigma_{F1}^2+\sigma_n^2)}\right)I_0\left(\frac{m\sqrt{y}}{\sigma_{F1}^2+\sigma_n^2}\right) \quad (19)$$

and

$$p_R(y|H_0) = \frac{1}{2(\sigma_{F0}^2+\sigma_n^2)}\exp\left(-\frac{y}{2(\sigma_{F0}^2+\sigma_n^2)}\right) \quad (20)$$

where $m^2 = S_I^2 + S_Q^2 = \alpha^2 M^2 T_c^2 S$. Using the orthogonal assumption previously mentioned in Section 3.1, the variance of the output of each of the MF correlators in MF_R can be denoted as $\sigma_R^2 = \sigma_{F0}^2 + \sigma_n^2$, and the PDF of R_K, is the χ^2 distribution with $2M$ degrees of freedom. This can be written as

$$p_{R_{K_i}}(z) = \frac{K_i^{2M}}{(2\sigma_R^2)^{2M}\Gamma(2M)} z^{2M-1}\exp\left\{-\frac{K_i z}{2\sigma_R^2}\right\}, \quad i=1,2 \quad (21)$$

For the considered fading channel, P_{DS} and P_{MS} can be given by

$$P_{DS} = \sum_{n=0}^{2L-1}(-1)^n\binom{2L-1}{n}\Bigg[\frac{C}{D_n}\exp\left\{-\frac{nM\gamma_c}{D_n(1+\Gamma)}\right\} - \exp\left\{-\frac{M\gamma_c(n+K_1)}{(D_n+K_1D)(1+\Gamma)}\right\}\sum_{k=0}^{2M-1}\left(\frac{K_1D}{D_n+K_1D}\right)^{k+1} F\left(-k,\ 1\ ;-\frac{CM\gamma_c}{(1+\Gamma)(D_n+K_1D)D}\right)\Bigg] \quad (22)$$

and

$$P_{MS} = \sum_{n=0}^{2L-1}(-1)^n\binom{2L-1}{n}\Bigg[\left(\frac{K_1}{K_1+n}\right)^{2M} - \left(\frac{K_1D}{D_n+K_1D}\right)^{2M} \cdot \exp\left\{-\frac{M\gamma_c(n+K_1)}{(1+\Gamma)(D_n+K_1D)}\right\}\sum_{k=0}^{\infty}\frac{1}{k!}\left\{\frac{M\gamma_c}{(1+\Gamma)D}\right\}^k \cdot F\left(k-2M+1,\ k+1\ ;-\frac{CM\gamma_c}{(1+\Gamma)(D_n+K_1D)D}\right)\Bigg] \quad (23)$$

where $\Gamma = 2\beta^2\sigma_s^2/\alpha^2$ is the power ratio of the fading component to the specular component, $\gamma_c = \alpha^2 ST_c(1+\Gamma)/N_0$ is the total received signal-to-noise ratio (SNR/chip), $C = \gamma_c\Gamma/(1+\Gamma)+1$, $D = \gamma_c W\Gamma/M(1+\Gamma)+1$, and $D_n = C + nD$. Ssubstituting (19), (20), and (21) into (10) and (11), one can get P_C and P_{FC} for the fading channel

$$P_C = 1 - \frac{C}{K_2D}\exp\left\{-\frac{K_2M\gamma_c}{(1+\Gamma)(C+K_2D)}\right\} \cdot \sum_{k=0}^{2M-1}\left(\frac{K_2D}{C+K_2D}\right)^{k+1} F\left(-k,\ 1\ ;-\frac{CM\gamma_c(1+\Gamma)^{-1}}{(C+K_2D)D}\right) \quad (24)$$

and

$$P_{FC} = 1 - \frac{1}{K_2}\sum_{k=0}^{2M-1}\left(\frac{K_2}{1+K_2}\right)^{k+1} \quad (25)$$

From (14), (24), and (25), we can get P_{CD} and P_{FCD} for the fading channel. To get the mean acquisition time for nonselective Rician fading channel, the expressions derived above for P_{DS}, P_{CD}, P_{FS}, P_{FCD}, and P_{MS} have to be substituted in (15).

Ⅳ. Numerical Results

In evaluating the precision of the statistical analysis for the decision threshold and the performance of the parallel acquisition system with reference filtering, we

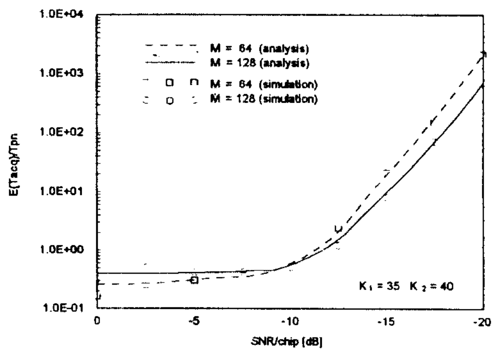

Fig. 2 Mean acquisition time for the nonfading channel

used the following parameters, namely: 1) $L=1023$ chips, 2) $M=64$, 93, and 128 chips, 3) the parameters A and B are set to be 4 and 2, respectively [9], 4) the correlation coefficients ρ_i are taken as ρ^i [7], and 5) $J=10000$ chips.

Fig. 2 shows the mean acquisition time for the nonfading channel for $M=64$ and 128. It is shown from Fig. 2 that the mean acquisition time from analysis obtained using the statistical evaluation of the threshold agrees well with the simulation. Also, it is shown that in the nonfading channel, for SNR <-10 [dB], it is advantageous to increase the MF length M, i.e., decrease the number of parallel MF's.

The comparison between the approximation of the decision threshold adopted in [2, 3] and the statistical analysis of the decision threshold is given for the nonselective Rician fading channel in terms of the mean acquisition time performance. For simplicity, the same weighting factor of the search and the verification modes is used, i.e., $K_1=K_2=K$. Fig. 3 shows the comparison results in terms of the mean acquisition time performance. For the results shown, the mean acquisition time has been normalized by $T_{pn}=LT_c$. In the considered fading channel ($\Gamma=0.1$ and $\Gamma=3.0$), it is observed that the approximation of the threshold value is reasonable for SNR >-8.5 [dB] and considerably different from the exact evaluation for SNR <-8.5 [dB]. This difference is more significant

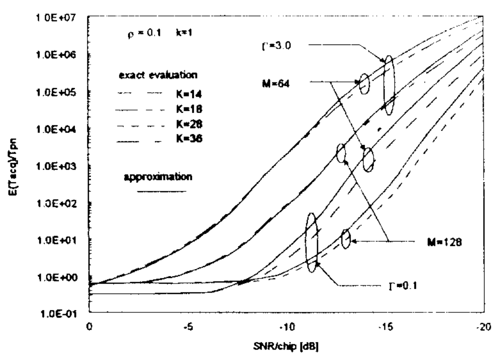

Fig. 3 Comparison between the approximation and the exact evaluation of the decision threshold

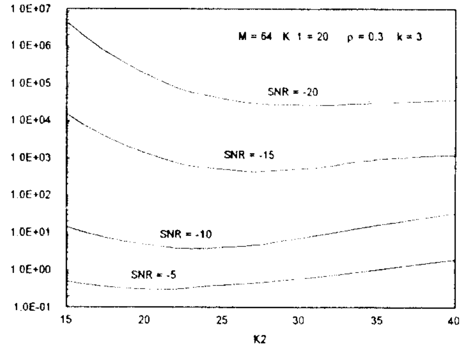

Fig. 4 Mean acquisition time versus K_2 for various values of SNR

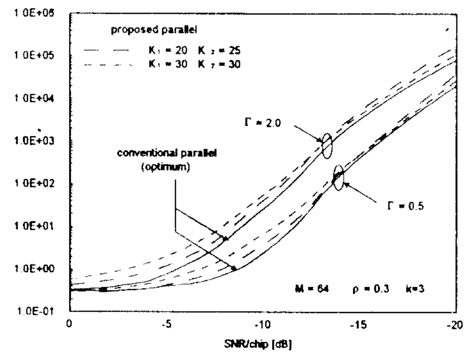

Fig. 5 Mean acquisition time for the Rician fading channel

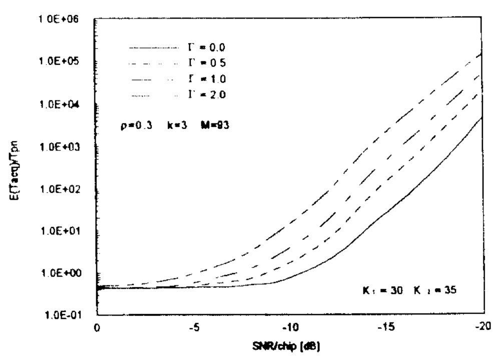

Fig. 6 Mean acquisition time for the Rician fading channel with Γ as a parameter

when M becomes smaller and when Γ becomes lower, i.e., when the specular component becomes stronger.

Fig. 4 shows the mean acquisition time versus the weighting factor K_2 for a fixed value of K_1 in the Rician fading channel. An immediate conclusion is that optimal values of weighting factors which minimize the mean acquisition time exist for each value of SNR/chip, but for a wide range of SNR the mean acquisition time is less sensitive to changes in K_2 about the optimum. It is also shown from Fig. 4 that for properly selected values of K_1 and K_2, the mean acquisition time is less affected by the variation of SNR/chip.

The performance comparison between the conventional parallel acquisition system described in [7] and the proposed parallel acquisition system is given for the nonselective Rician fading channels. Fig. 5 exhibits the mean acquisition time for the proposed and conventional parallel acquisition systems. For the conventional parallel system, the threshold values are selected numerically to minimize the mean acquisition time for each value of SNR/chip. For all values of SNR/chip, the weighting factors K_1 and K_2 are fixed at some values to give comparable mean acquisition time performance to the conventional parallel acquisition system. In the considered fading channels ($\Gamma = 0.5$ and $\Gamma = 2.0$), there is no need to determine threshold values for each value of SNR/chip if the proposed parallel acquisition system is used instead of the conventional parallel acquisition system. It is interesting to note that the proposed parallel system is less sensitive to the variations of K_1 and K_2.

Fig. 6 shows the effect of Γ on the mean acquisition time for the Rician fading channel. As expected, for lower values of ρ, the system is faster. It has also been noted by authors that variations of ρ and k are of negligible effect.

V. Concluding Remarks

This paper is concerned with the statistical analysis of the decision threshold for the DS-SS parallel acquisition system with a reference filter. The detection and false alarm probabilities are derived in both nonfading and nonselective Rician fading channels, and the mean acquisition time is evaluated as a performance measure.

The comparison between the approximation of the decision threshold adopted in [2, 3] and the statistical analysis of the decision threshold is given in terms of the mean acquisition time performance. The statistical results show that the statistical evaluation of the decision threshold is more reasonable in the performance nalysis of the parallel acquisition scheme with reference filtering than the approximation of the decision threshold adopted in other previous works [2, 3]. The proposed parallel acquisition system has been compared with the conventional parallel acquisition system. It is shown that with approximately the same degree of structuring complexity, the mean acquisition time of the proposed parallel system is comparable to the optimum mean acquisition time of the conventional parallel system.

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