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Detection Technique for Code Acquisition in DS-SS Systems Employing PN Matched Filters

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ABSTRACT

This paper presents a threshold decision technique for direct sequence code acquisition employing Pseudo-Noise (PN) matched filters. The probabilities of detection and false alarm are derived as a measure of the system performance in both nonfading and nonselective Rician fading channels. For received PN codes with different SNR, the proposed acquisition scheme is able to detect a desired threshold in the search mode so that this value is utilized as a threshold for the verification mode. Thus, there is no need to determine a threshold by applying the Neyman-Pearson criterion. It is shown that this scheme achieves lower probability of false alarm than the acquisition scheme based on the Neyman-Pearson criterion, giving comparable performance in terms of the probability of detection.

I. Introduction

The use of direct-sequence spread-spectrum (DS-SS) in mobile communications has been growing considerably over the past few years. DS-SS is especially attractive in this situation due to its inherent antimultipath capabilities [1]. Pseudo-Noise (PN) code synchronization 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 allows the recovery of data sequence. PN code synchronization is usually performed in two stages: code acquisition and code tracking. Code acquisition allows the phase between the incoming PN code and the local PN code to be within a small relative timing offset. The region of time/frequency uncertainty of the incoming PN code is divided into cells with one of them denoting the sync-cell (hypothesis H_1) and the others the nonsync cells (hypothesis H_0). Once code acquisition has been accomplished, a code tracking is employed to achieve fine alignment of the two sequences and maintain that alignment.

The performance of the acquisition scheme will depend on the setting of the threshold. In practice, a receiver has no prior knowledge about the signal-to-noise ratio (SNR) of any received PN code, thus the threshold is often determined by the Neyman-Pearson criterion in terms of some parameters [2-4]. For an acquisition scheme based upon the Neyman-Pearson criterion (the conventional acquisition scheme), if the threshold is set relatively low to the advantage of weak signals, the probability of false alarm will be increased. On the other hand, if the threshold is set relatively high to the advantage of large signals, the probability of miss will be increased. Thus, it is essential to determine an acquisition threshold with its value being set according to the SNR of the received PN code.

This paper is concerned with the performance analysis of a threshold decision for PN code acquisition

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using a maximum mismatched correlation value in DS-SS systems. This maximum mismatched correlation value is right below the largest correlation value in one PN period and is detected by means of a properly designed detection window in the search mode. This value is used to confirm the acquisition test in the verification mode, thus there is no need to determine a threshold by applying the Neyman-Pearson criterion. The probabilities of detection and false alarm are derived for the proposed scheme in both nonfading and nonselective Rician fading channels. The performance of the proposed acquisition scheme is compared with the acquisition scheme based upon the Neyman-Pearson criterion, and it is shown that the proposed scheme allows the false alarm probability to be kept well below an acceptable false alarm rate, giving comparable performance in terms of the detection probability.

II. System Description

The search mode, as shown in Fig. 1 (a), consists of an I-Q passive noncoherent PN matched filter (PNMF) and the detection window block. One of the I-Q PNMF's is shown in Fig. 1 (b) and its hardware is discussed in [3,4]. The number of taps on each delay line is M/Δ with ΔT_c delay between successive taps, where M is MF' length, Δ is a search step size, and T_c is the chip duration. The noncoherent detector makes a decision every ΔT_c seconds, i.e., at a multiple rate of the code rate T_c^{-1}; at the same time, the decision is based upon a correlation time of MT_c seconds. During the search mode, the switch is in position 1. When the size of detection window becomes equal to $M/\Delta - 1$, the switch that was in position 1 is put in position 2. Otherwise the switch is put in position 1 and the search procedure is resumed.

Let $R_k = R(k\Delta T_c)$ denote the correlation output from matched filter at t_k and w_k denote the detection window initiated by R_k. The proposed scheme utilizes two PN periods to detect a maximum mismatched correlation value R_{MMC} and sets this value as a threshold for the verification mode. To do this, we design a detection window. The detection window w_k will be initiated whenever the condition $R_1 < R_k$, $R_2 < R_k$, $\cdots$, $R_{k-1} < R_k$ is satisfied. Denote the detection windows initiated by H_1 and H_0 cells by the correct detection window and the false detection window, respectively. The proposed acquisition procedure is as follows.

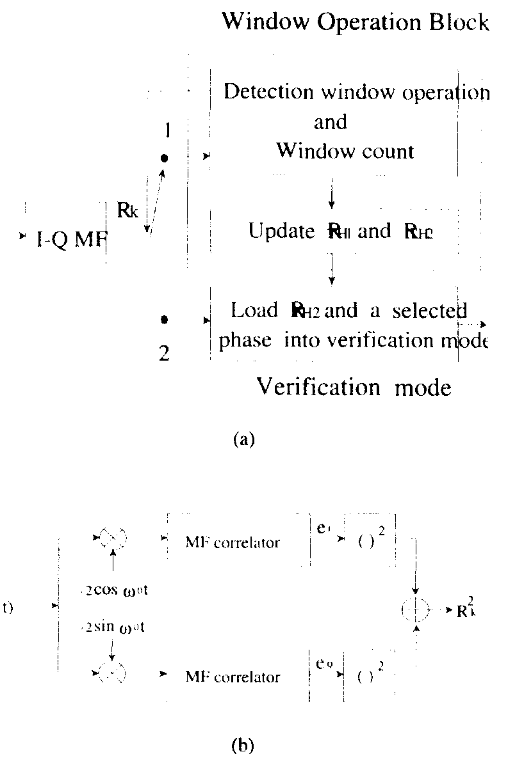

Fig. 1 (a) Acquisition circuit block diagram (b) I-Q noncoherent MF

[1] Initialize R_{TH1} and R_{TH2} to zero.

[2] Compare R_k with R_{TH1} and R_{TH2} every ΔT_c seconds. If R_k is greater than R_{TH1} open a detect-

ion window (equivalently, initialize window size to zero), store R_k in R_{TH1}, and set R_{TH2} to zero. If R_k is smaller than R_{TH1} and greater than R_{TH2} keep the detection window open and store R_k in R_{TH2}. The detection window is incremented by one every ΔT_c seconds.

[3] Repeat the step 2 until the window size becomes equal to $M/\Delta - 1$.

[4] When the window size equals to $M/\Delta - 1$, go to the verification mode and set R_{TH2} as a threshold for verification otherwise and continue the search procedure.

The function of the verification mode is to avoid a costly false alarm that can supply the tracking system with a wrong phase. In the verification mode, a coincidence detection (CD) similar to [3,5] is used to verify the selected phase by the search mode. When a threshold and a phase are selected by the search mode, they are loaded into the verification mode. The receiver advances this local phase by the same rate as the incoming PN code. At the end of a CD, if at least B of A CD tests are larger than the threshold decided in the search mode, R_{MMC}, acquisition is declared and the tracking system is initiated, otherwise the system goes back to the search mode. The statistical independence of the A successive CD tests is assured by the use of disjoint MT_c -second intervals for each test.

III. Performance Analysis

3.1 Nonfading channel

In deriving the probability expressions, we shall adopt the following assumptions used in [2,5]. 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 $(0-2\pi)$, w_0 is the carrier frequency, $c(t+\tau T_c)$ is the code to be acquired, and $n(t)$ represents AWGN with one-sided power spectral density N_0 and zero mean. The inphase and quardrature variable e_I and e_Q are given by (neglecting double-frequency terms)

$$e_I = y\cos\theta + N_I \quad \text{and} \quad e_Q = y\sin\theta + N_Q \tag{2}$$

with

$$y = \sqrt{S}\int_0^{MT_c} c(t+\tau T_c)\, c(t+\zeta T_c)\, dt \tag{3}$$

where N_I and N_Q are zero mean Gaussian random variables with variance $\sigma_n^2 = N_0 M T_c/2$ and y is the correlation between the incoming PN code and the local PN code in the matched filter. For large M and full code correlation, the self-noise term is negligibly small and can be ignored [2].

The detection probability and the false alarm probability of the search mode are the probabilities that the size of detection window equals to $M/\Delta - 1$ under both hypothesis H_1 and H_0. The probability density function (pdf) of $R_k = \sqrt{e_I^2 + e_Q^2}$ under H_1 and H_0 follows the Rician and Rayleigh distributions, respectively. These are given by [10]

$$p_R(y|H_1) = \frac{y}{\sigma_n^2}\exp\left(-\frac{y^2+m^2}{2\sigma_n^2}\right) I_0\left(\frac{ym}{\sigma_n^2}\right) \tag{6}$$

and

$$p_R(y|H_0) = \frac{y}{\sigma_n^2}\exp\left(-\frac{y^2}{2\sigma_n^2}\right) \tag{7}$$

where $I_0(x)$ is the modified Bessel function of first kind and zero order, and $m^2 = M^2 T_c^2 S$. The detection probability of the search mode P_{D1} is given by

$$P_{D1} = \frac{1}{M/\Delta} \sum_{k=0}^{M/\Delta-1} P_{C_k} \tag{8}$$

where P_{C_k} is the probability that the detection window w_k is initiated by an H_1-cell and stays open for $M/\Delta - 1$ samples, which can be written as

$$P_{C_k} = \int_0^\infty p_R(y|H_1)\left[\int_0^y p_R(z|H_0)dz\right]^{M/\Delta+k-1} dy\,. \tag{9}$$

Substituting (6) and (7) into (9), and integrating, yields

$$P_{C_k} = \sum_{n=0}^{M/\Delta+k-1}(-1)^n \binom{M/\Delta+k-1}{n}\frac{1}{n+1} \exp\left[-\left(\frac{n}{n+1}\right)M\gamma_c\right] \tag{10}$$

where $\gamma_c = ST_c/N_o$ is the SNR/chip. The false alarm probability of the search mode P_{FA1} can be written as

$$P_{FA1} = \frac{1}{M/\Delta}\sum_{k=0}^{M/\Delta-1} P_{F_k} \tag{11}$$

where P_{F_k} is the probability that the detection window w_k is initiated by H_0-cells and stays open for $M/\Delta - 1$ samples, which can be written as

$$\begin{aligned} P_{F_k} = {} & \frac{k}{M/\Delta-1}\int_0^\infty p_R(y|H_0)\left[\int_0^y p_R(z|H_1)\,dz\right]^2 \left[\int_0^y p_R(z|H_0)\,dz\right]^{M/\Delta+k-3} dy \\ & + \frac{M/\Delta-k-1}{M/\Delta-1}\int_0^\infty p_R(y|H_0)\left[\int_0^y p_R(z|H_1)\,dz\right] \left[\int_0^y p_R(z|H_0)\,dz\right]^{M/\Delta+k-2} dy\,. \end{aligned} \tag{12}$$

Substituting (6) and (7) into the first integral term and the second integral term in (12), and adapting an approach similar to that in [9, p. 398], yields, respectively

$$\begin{aligned} & \int_0^\infty p_R(y|H_0)\left[\int_0^y p_R(z|H_1)dz\right]^2\left[\int_0^y p_R(z|H_0)dz\right]^{M/\Delta+k-3} dy \\ & = \sum_{n=0}^{M/\Delta+k-3}(-1)^n\binom{M/\Delta+k-3}{n}\frac{2}{(n+1)(n+2)} \exp\left[-\left(\frac{n+1}{n+2}\right)M\gamma_c\right] \\ & \times\left[1 - Q(\sqrt{2a},\sqrt{2b}) + \frac{1}{n+3}\exp\{-(a+b)\}I_0(2\sqrt{ab})\right] \end{aligned} \tag{13}$$

and

$$\begin{aligned} & \int_0^\infty p_R(y|H_0)\left[\int_0^y p_R(z|H_1)\,dz\right]\left[\int_0^y p_R(z|H_0)\,dz\right]^{M/\Delta+k-2} dy \\ & = \sum_{n=0}^{M/\Delta+k-2}(-1)^n\binom{M/\Delta+k-2}{n}\frac{1}{(n+1)(n+2)} \exp\left[-\left(\frac{n+1}{n+2}\right)M\gamma_c\right] \end{aligned} \tag{14}$$

where $a = \left(\frac{n+2}{n+3}\right)M\gamma_c$, $b = \frac{1}{(n+2)(n+3)}M\gamma_c$, and $Q(\cdot,\cdot)$ is the Marcum's Q function [10, p. 585].

The function of the verification mode is described earlier. When the verification mode is initiated by a correct phase, the probability of accepting it, is given by

$$P_{D2} = \sum_{n=B}^{A}\binom{A}{n} P_1^{\,n}(1-P_1)^{A-n} \tag{15}$$

while the verification mode is initiated by a false phase, the probability of accepting it, is given by

$$P_{FA2} = \sum_{n=B}^{A}\binom{A}{n} P_2^{\,n}(1-P_2)^{A-n} \tag{16}$$

where P_1 and P_2 are the probabilities that an H_1 and H_0 cells exceed R_{MMC} decided in the search mode by the proposed scheme, respectively, which are given by

$$P_1 = \int_0^\infty p_R(y|H_1)\int_0^y p_{R_{MMC}}(z|H_1)\,dz\,dy \tag{17}$$

and

$$P_2=\int_0^{\infty} p_R(y|H_0)\int_0^{y} p_{R_{MMC}}(z|H_0)\,dzdy. \quad (18)$$

In (17) and (18), $p_{R_{MMC}}(z|H_1)$ is the pdf of R_{MMC} detected by the correct detection window, which is given by

$$p_{R_{MMC}}(y|H_1) = \frac{d}{dy}\left[\left\{1-\exp\left(-\frac{y^2}{2\sigma_n^2}\right)\right\}^{M/\Delta-1}\right]$$
$$=(M/\Delta-1)\sum_{n=0}^{M/\Delta-2}(-1)^n\binom{M/\Delta-2}{n}\frac{y}{\sigma_n^2} \quad (19)$$
$$\exp\left\{-\frac{(n+1)y^2}{2\sigma_n^2}\right\}$$

and $p_{R_{MMC}}(z|H_0)$ is the pdf of R_{MMC} in the false detection window, which is given by

$$p_{R_{MMC}}(y|H_0) = \frac{d}{dy}\left[\left\{1-Q\left(\frac{m}{\sigma_n},\frac{y}{\sigma_n}\right)\right\}\left\{1-\exp\left(-\frac{y^2}{2\sigma_n^2}\right)\right\}^{M/\Delta-2}\right]$$
$$=\Big[(M/\Delta-2)\left\{1-Q\left(\frac{m}{\sigma_n},\frac{y}{\sigma_n}\right)\right\}$$
$$+\exp\left(-\frac{m^2}{2\sigma_n^2}\right)\left\{1-\exp\left(-\frac{y^2}{2\sigma_n^2}\right)\right\}\times I_0\left(\frac{my}{\sigma_n^2}\right)\Big]$$
$$\sum_{n=0}^{M/\Delta-3}(-1)^n\binom{M/\Delta-3}{n}\frac{y}{\sigma_n^2}\exp\left\{-\frac{(n+1)y^2}{2\sigma_n^2}\right\} \quad (20)$$

Substituting (19) and (20) into (17) and (18), one can get

$$P_1=\sum_{n=0}^{M/\Delta-1}(-1)^n\binom{M/\Delta-1}{n}\frac{1}{n+1}\exp\left[-\left(\frac{n}{n+1}\right)M\gamma_c\right] \quad (21)$$

$$P_2=\sum_{n=0}^{M/\Delta-2}(-1)^n\binom{M/\Delta-2}{n}\frac{1}{(n+1)(n+2)}$$
$$\exp\left[-\left(\frac{n+1}{n+2}\right)M\gamma_c\right]. \quad (22)$$

We can clearly see that at low SNR/chip, P_2 reaches a maximum value. From (22), this maximum is

$$\sum_{n=0}^{M/\Delta-2}(-1)^n\binom{M/\Delta-2}{n}\frac{1}{(n+1)(n+2)}=\frac{1}{M/\Delta}. \quad (23)$$

3.2 Rician Fading Channel

In our analysis we consider a nonselective Rician fading channel described in [9], 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. From [9], under hypothesis $H_i: i=0, 1$, e_I and e_Q follow the zero-mean gaussian distribution with variances $\sigma_0{}^2=\beta^2 SMT_c^2\sigma_s^2+\sigma_n^2$ and $\sigma_1{}^2=\beta^2 SWT_c^2\sigma_s^2+\sigma_n^2$, respectively, where W is the conditional variance of a correct cell normalized by in-phase (or quadrature) signal variance as defined in [5]. For the case of a considered channel, the pdf of R_k follows (6) and (7) with σ_n^2 replaced by σ_0^2 and σ_1^2, respectively. $p_{R_{MMC}}(y|H_1)$ and $p_{R_{MMC}}(y|H_0)$ for the considered nonselective Rician fading channel can be written as

$$p_{R_{MMC}}(y|H_1)=(M/\Delta-1)\sum_{n=0}^{M/\Delta-2}(-1)^n\binom{M/\Delta-2}{n}\frac{y}{\sigma_0^2}$$
$$\exp\left\{-\frac{(n+1)y^2}{2\sigma_0^2}\right\} \quad (24)$$

and

$$p_{R_{MMC}}(y|H_0)=\Big[(M/\Delta-2)\left\{1-Q\left(\frac{m}{\sigma_1},\frac{y}{\sigma_1}\right)\right\}\frac{y}{\sigma_0^2}\exp\left(\frac{y^2}{2\sigma_0^2}\right)$$
$$+\frac{y}{\sigma_1^2}\exp\left(-\frac{y^2+m^2}{2\sigma_1^2}\right)$$
$$\times\left\{1-\exp\left(-\frac{y^2}{2\sigma_0^2}\right)\right\}I_0\left(\frac{my}{\sigma_1^2}\right)\Big]\sum_{n=0}^{M/\Delta-3}(-1)^n\binom{M/\Delta-3}{n}$$
$$\exp\left(-\frac{ny^2}{2\sigma_0^2}\right). \quad (25)$$

Substituting these pdfs into (18) and (19), one can get P_1 :

$$P_1 = \sum_{n=0}^{M/\Delta-1} (-1)^n \binom{M/\Delta-1}{n} \frac{C}{C+nD} \exp\left\{-\frac{nM\gamma_c}{(1+\Gamma)(C+nD)}\right\} \quad (26)$$

and

$$P_2 = \sum_{n=0}^{M/\Delta-2} (-1)^n \binom{M/\Delta-2}{n} \frac{C}{(n+1)\{C+(n+1)D\}} \exp\left[-\frac{(n+1)M\gamma_c}{(1+\Gamma)\{C+(n+1)D\}}\right] \quad (27)$$

where Γ is the power ratio of the fading component to the specular component, $C=\gamma_c\Gamma/(1+\Gamma)+1$, and $D=\gamma_c W\Gamma/M(1+\Gamma)+1$. Similarly, the mathematical expressions for P_{D1} and P_{FA1} in the considered fading channel can be obtained.

IV. Detection Performance Results

As an application for the proposed acquisition system, we used the following parameters, namely: 1) PN code of length (M) of 63, 127, and 255 are considered, 2) Δ=1/2, 3) the parameters A and B for the verification mode are set to be 4 and 2, respectively [3], 4) the correlation coefficients ρ_i are taken as ρ^i [5], 5) the penalty factor due to false alarm is set to $1000MT_c$, and 6) only full code correlation is considered.

Table 1 exhibits the upper values of false alarm probability P_{FA2} for the proposed scheme. To obtain large P_{D2}, the false alarm probability approaches unit for the conventional acquisition scheme, whereas the false alarm probability approaches a constant value for the proposed acquisition scheme as shown in (23). From this result, it is clear that as SNR decreases, the false alarm probability for the proposed scheme does not exceed the calculated upper value in Table 1 at low SNR. Fig. 2 shows the overall false alarm and detection probabilities for the proposed scheme with parameter M equal to 63, 127, and 255 in the nonfading channel.

Table 1. Upper values of P_{FA2} for $M=63$, 127, and 255 (Δ=1/2)

M	63	127	255
P_{FA2}	0.000368	0.000092	0.000023

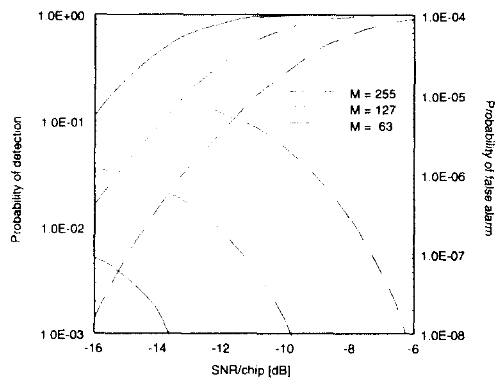

Fig. 2 Overall probabilities of false alarm and detection

The performance comparison between the conventional acquisition scheme (based upon the Neyman-Pearson criterion) and the proposed acquisition scheme is given for the nonfading channel. Fig. 3 presents the probabilities of detection and false alarm for the proposed and conventional schemes. It is shown from Fig. 3 that when the upper values of P_{FA2} is set to an acceptable false alarm rate for the conventional scheme, the proposed scheme gives comparable performance with the conventional scheme in terms of P_{D2} for a wide range of SNR. Moreover, the conventional scheme maintains P_{FA2} at a constant value, 0.000092, even at high SNR, respectively, whereas the proposed scheme allows P_{FA2} to be decreased well below the constant value.

Fig. 4 shows the probabilities of detection and false alarm for both the nonfading and nonselective Rician channels with Γ as a parameter. A severe

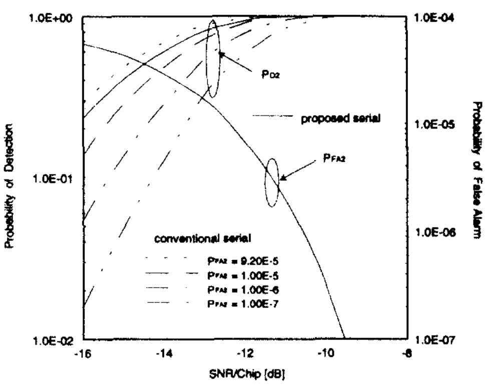

Fig. 3 Probabilities of detection and false alarm for the conventional scheme and the proposed scheme in verification mode (M = 127)

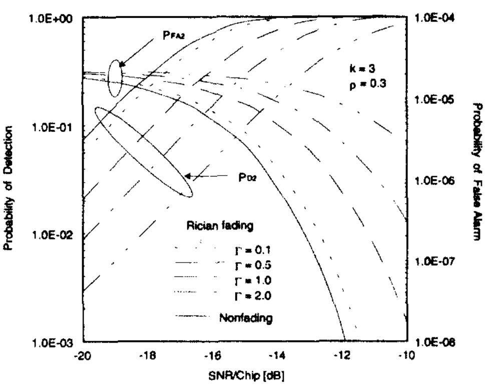

Fig. 4 Probabilities of detection and false alarm for both nonfading and Rician fading channels in verification mode (M = 255)

degradation in the probabilities of detection and false alarm due to the fading channel can be observed. As expected, for lower values of Γ, the probabilities of detection and false alarm approach those of the nonfading channel.

Fig. 5 shows the mean acquisition time versus SNR/chip for both the nonfading and Rician fading channels. It is shown that in the nonfading channel, for SNR<-9 [dB], it is advantageous to increase the MF' length M as big as practically possible. A severe degradation in the mean acquisition times due to fading conditions can be observed, which raises some doubts about the ability of the proposed system to work in such channels when frequency selectivity and code Doppler are taken into considerations.

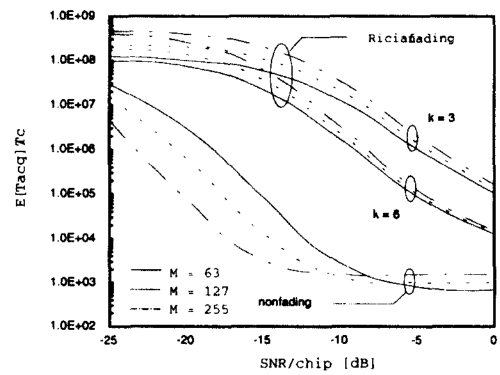

Fig. 5 Mean acquisition time for nonfading and Rician fading channels

V. Concluding remarks

A threshold decision technique using a maximum mismatched correlation value for PN code acquisition is proposed and analyzed for such key system parameters as probabilities of false alarm and detection for both nonfading and nonselective Rician fading channels. A severe degradation in the probabilities of detection and false alarm due to the fading channel can be observed.

By means of the detection window operation the proposed scheme guarantees the desired threshold setting for verification, which enables us not to determine a threshold for verification by applying the Neyman-Pearson criterion. It is also shown that this scheme achieves lower probability of false alarm than the conventional acquisition scheme, giving comparable performance in terms of the detection probability.

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