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Detection of M-ary Signals for Ultra Wideband Multiple Access Systems

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Abstract

In this paper, we propose a novel detection criterion for weak M-ary signal detection. In the sense of minimizing the error probability, the proposed novel detection criterion is optimum when the signal strength approaches zero. Based on the proposed novel detection criterion, a new detector for ultra wideband multiple access systems is proposed in the presence of impulsive interference modeled with the bivariate isotropic symmetric α-stable distribution. Numerical results show that the proposed detector possesses less complexity than and about the same performance as the detector optimized for the Cauchy distribution. In impulsive interference, the proposed detector also offers substantial performance improvement over the detector optimized for the Gaussian distribution.

KEY WORDS

Locally optimum, M-ary signals, Detector, UWB, Stable distribution, Impulsive interference

1 Introduction

Recently, with significant interest and attention to developing low power communication systems, the importance of weak signal detection keeps growing. In situations where the signal is vanishingly small, it is desirable to design a detector which has optimum performance at low signal-to-noise ratio (SNR). As a way to obtain such a detector, detection schemes based on the locally optimum (LO) detection criterion [1]-[3] can be used.

Since the LO detection criterion is derived originally for the detection of binary signals, we propose a novel detection criterion which can be used also for weak M-ary signal detection by extending the binary LO detection criterion. The proposed novel detection criterion results in simple detector structures especially in non-Gaussian, impulsive noise environment and is optimum in the region where the signals are of weak strength. Here, the term 'optimum' is in the sense of minimum error probability unlike in the binary LO detection criterion.

Based on the proposed novel detection criterion, we propose a new detector for ultra wideband multiple access

(UWB-MA) systems [4] in the presence of the bivariate isotropic symmetric α-stable (BISαS) impulsive interference [5], [6]. The performance of the proposed detector is then examined in comparison with the detectors optimized for the Cauchy and Gaussian distributions in the sense of minimum error probability. From computer simulations, it is observed that the performance of the proposed detector barely differs from that of the Cauchy-optimized detector although the proposed detector is a low-complexity version of the Cauchy-optimized detector allowing simpler structures. Furthermore, computer simulations also show that the proposed detector generally outperforms the Gaussian-optimized detector in impulsive environment such as the family of the BISαS impulsive interference.

2 Novel detection criterion for weak M-ary signals

2.1 Observation model

Suppose an original signal $s_i(t)$, an element of the set $\{s_i(t)\}_{i=1}^M$ of M possible signals, has passed through an additive noise channel. Then, the received signal $r(t)$ may be expressed as

$$\begin{aligned} r(t) &= s_i(t) + n(t) \\ &= \theta_i \tilde{s}_i(t) + n(t), \ 0 \le t \le T_s. \end{aligned} \tag{1}$$

In (1), $n(t)$ is the sample function of the additive noise process,

$$\theta_i = \sqrt{\int_0^{T_s} |s_i(t)|^2 dt} \tag{2}$$

is the signal strength (the square root of the energy) of the signal $s_i(t)$, $\tilde{s}_i(t)$ represents the unit energy version of $s_i(t)$, and T_s is the signal duration. We will assume that the signal strength can be expressed as

$$\theta_i = \theta\epsilon_i \tag{3}$$

for $i = 1, 2, \cdots, M$, where θ is the common factor of the signal strength θ_i and ϵ_i is a non-negative proportionality constant for the signal strength θ_i of the signal $s_i(t)$. We can then control the strengths of all signals by the common parameter θ.

It is assumed that the signal space is spanned by N orthonormal basis functions $\{\psi_k(t)\}_{k=1}^N$. In other words, for any signal $s_i(t) \in \{s_i(t)\}_{i=1}^M$, there exist real numbers $\{c_{ki}\}_{k=1}^N$ such that $s_i(t) = \sum_{k=1}^N c_{ki}\psi_k(t)$. Then, by projecting $r(t)$ onto the N orthonormal basis functions, we have

$$\begin{aligned} r_k &= \int_0^{T_s} r(t)\psi_k(t)dt \\ &= \int_0^{T_s} [s_i(t) + n(t)]\psi_k(t)dt \\ &= \theta\epsilon_i s_{ik} + n_k, \ k = 1, 2, \cdots, N, \end{aligned} \tag{4}$$

where

$$s_{ik} = \int_0^{T_s} \tilde{s}_i(t)\psi_k(t)dt, \ k = 1, 2, \cdots, N \tag{5}$$

and

$$n_k = \int_0^{T_s} n(t)\psi_k(t)dt, \ k = 1, 2, \cdots, N. \tag{6}$$

From (4)-(6), the observation vector $\mathbf{r} = (r_1, r_2, \cdots, r_N)$ of correlator outputs can be expressed as

$$\mathbf{r} = \theta\epsilon_i \mathbf{s}_i + \mathbf{n}, \tag{7}$$

where $\mathbf{s}_i = (s_{i1}, s_{i2}, \cdots, s_{iN})$ and $\mathbf{n} = (n_1, n_2, \cdots, n_N)$.

2.2 Proposed detection criterion

Suppose that the M-ary signals $\{s_i(t)\}_{i=1}^M$ are equiprobable. The probability $P_e(\theta)$ of symbol error is then given as

$$P_e(\theta) = 1 - \frac{1}{M}\sum_{i=1}^M \int_{D_i} p(\mathbf{r}|s_i, \theta)d\mathbf{r}, \tag{8}$$

where $p(\mathbf{r}|s_i, \theta)$ represents the conditional probability density function (pdf) of $\mathbf{r}$ given that $s_i(t)$ is transmitted and the value of the signal strength parameter is θ, and D_i is the decision region over which we decide $s_i(t)$ is sent. Here, $\{D_i\}_{i=1}^M$ is a partition of the N-dimensional real vector space $\mathbb{R}^N$. If $\theta = 0$, $p(\mathbf{r}|s_i, 0)$ is equal to the joint pdf $p_{\mathbf{n}}(\mathbf{r})$ of $\mathbf{n}$ for $i = 1, 2, \cdots, M$ from (7). Thus, we have

$$\begin{aligned} P_e(0) &= 1 - \frac{1}{M}\sum_{i=1}^M \int_{D_i} p(\mathbf{r}|s_i, 0)d\mathbf{r} \\ &= 1 - \frac{1}{M}\int_{\mathbb{R}^N} p_{\mathbf{n}}(\mathbf{r})d\mathbf{r} \\ &= 1 - \frac{1}{M} \end{aligned} \tag{9}$$

from (8). Note that $P_e(0)$ is a constant and independent of the detection criterion. Based on this observation, we have the following.

Proposition 1 *When the signal strength approaches zero, $P_e(\theta)$ is minimized if*

$$\begin{aligned} D_i = \Bigg\{\mathbf{r} : \frac{\partial}{\partial\theta} p(\mathbf{r}|s_i, \theta)\bigg|_{\theta=0} \\ \ge \frac{\partial}{\partial\theta} p(\mathbf{r}|s_j, \theta)\bigg|_{\theta=0}, \forall j\Bigg\} \end{aligned} \tag{10}$$

for $i = 1, 2, \cdots, M$.

Proof: Since

$$P_e(\theta) \approx P_e(0) + \theta\,\frac{\partial}{\partial\theta}P_e(\theta)\bigg|_{\theta=0}, \tag{11}$$

a detection criterion which makes $\frac{\partial}{\partial\theta}P_e(\theta)\big|_{\theta=0}$ minimized results in the minimum $P_e(\theta)$ when θ is close to zero. Now, since

$$\frac{\partial}{\partial\theta}P_e(\theta)\bigg|_{\theta=0} = -\frac{1}{M}\sum_{i=1}^{M}\int_{D_i}\frac{\partial}{\partial\theta}p(\mathbf{r}|s_i,\theta)\bigg|_{\theta=0} d\mathbf{r}, \quad (12)$$

$\frac{\partial}{\partial\theta}P_e(\theta)\big|_{\theta=0}$ is minimized if D_i is chosen as specified in (10). *Q.E.D.*

In essence, we have obtained a detection criterion: the decision region (10) tells us that when the signal strength parameter θ is close to zero, $P_e(\theta)$ is minimized by deciding $s_i(t)$ if $\frac{\partial}{\partial\theta}p(\mathbf{r}|s_i,\theta)\big|_{\theta=0}$ is larger than or equal to $\frac{\partial}{\partial\theta}p(\mathbf{r}|s_j,\theta)\big|_{\theta=0}$ for all j.

2.3 Example of the decision region

Let us obtain a specific example of the detection region based on the proposed criterion. Assume that the noise components in (7) are independent and identically distributed (i.i.d.) t-distributed random variables. The t-distribution arises naturally in sampling from a Gaussian distributed population [3]. Now, the conditional pdf of $\mathbf{r}$ is

$$p(\mathbf{r}|s_i,\theta) = \prod_{k=1}^{N} f(r_k - \theta\epsilon_i s_{ik}), \quad (13)$$

where

$$f(x) = \frac{\Gamma\left((\nu+1)/2\right)}{\sqrt{\pi\nu}\Gamma(\nu/2)}(1+\frac{x^2}{\nu})^{-\frac{\nu+1}{2}} \quad (14)$$

is the t-distributed pdf with degree of freedom ν. With

$$\frac{\partial}{\partial\theta}p(\mathbf{r}|s_i,\theta)\bigg|_{\theta=0} = \prod_{k=1}^{N} f(r_k)\sum_{k=1}^{N}\frac{(\nu+1)\epsilon_i r_k s_{ik}}{\nu+r_k^2}, \quad (15)$$

the proposed criterion results in the decision region

$$D_i^P = \left\{\mathbf{r} : \sum_{k=1}^{N}\frac{\epsilon_i r_k s_{ik}}{\nu+r_k^2} \geq \sum_{k=1}^{N}\frac{\epsilon_j r_k s_{jk}}{\nu+r_k^2}, \forall j\right\}. \quad (16)$$

Note that the proposed decision region D_i^P in (16) does not require an estimate of the value of θ. On the other hand, for the same detection problem, the maximum-likelihood (ML) criterion results in the decision region

$$\begin{aligned} D_i^{ML} = & \left\{\mathbf{r} : \prod_{k=1}^{N}\left(\nu + (r_k - \theta\epsilon_i s_{ik})^2\right)\right. \\ & \left.\leq \prod_{k=1}^{N}\left(\nu + (r_k - \theta\epsilon_j s_{jk})^2\right), \forall j\right\} (17)\end{aligned}$$

The ML decision region D_i^{ML} in (17) clearly depends on θ. This implies that the value of θ has to be estimated in real communication environments. Therefore, we can see that the proposed criterion has a reduced burden for realization in comparison with the ML criterion.

In addition, we shall see in the following section that there is almost no difference in performance between the detectors using the proposed and ML criteria. Furthermore, if the detector based on the ML criterion estimate the value of θ inaccurately, its performance would be far from the optimum and could be worse than the performance of the detector based on the proposed criterion.

3 Application of the proposed criterion to ultra wideband multiple access systems

3.1 System model

Assume that the users employ binary pulse position modulation (PPM) in which the transmitted signals consist of a low duty-cycle sequence of a number of ultra wideband (UWB) pulses. The duration T_q of the unit energy UWB pulse $q(t)$ is only a very small portion of the frame time (or pulse repetition period) T_f. The l-th user's signal for $0 \leq t \leq N_s T_f$ is one of the two equi-probable signals $\{s_i^{(l)}(t)\}_{i=1}^{2}$, where

$$s_i^{(l)}(t) = \tilde{\theta}\sum_{k=0}^{N_s-1} q(t - kT_f - c_k^{(l)}T_c - d_i^{(l)}\frac{T_c}{2}). \quad (18)$$

In (18), $N_s T_f$ is the symbol duration, $\tilde{\theta}$ is the value of the signal strength parameter when the signal is transmitted, N_s is the number of the UWB pulses modulated by a given symbol, T_c is the chip duration ($T_c > 2T_q$), $\{c_k^{(l)}\}$ is a time-hopping sequence of values $c_k^{(l)} \in \{0, 1, \cdots, N_h\}$ for the l-th user with period N_c (i.e., $c_{k+jN_c}^{(l)} = c_k^{(l)}$, $\forall$integers k, j), and $\{d_i^{(l)}\}$ is the data sequence of the l-th user ($d_1^{(l)} = 0$ and $d_2^{(l)} = 1$). The frame time T_f is chosen to be sufficiently large ($T_f > N_h T_c + T_c$) to reduce intersymbol and intrasymbol interference caused by the delay spread.

When the UWB-MA system has N_u users ($N_u \leq N_c$), the received signal $r(t)$ is given as

$$r(t) = \sum_{l=1}^{N_u} s_{rec}^{(l)}(t) + \tilde{n}(t), \quad (19)$$

where $s_{rec}^{(l)}(t)$ is the l-th user's signal arrived at the receiver and $\tilde{n}(t)$ denotes the channel noise. Let us assume that there is no signal distortion due to the propagation through the channel and the receiver is interested in determining the data sent by the first user.

The received signal $r(t)$ given that $s_i^{(1)}(t)$ is transmitted can then be expressed as

$$r(t) = A_1 s_i^{(1)}(t-\tau_1) + n(t), \quad (20)$$

where τ_1 represents the time delay between the transmitter of the first user and the receiver, A_1 models the attenuation of the first user's signal over the propagation path to the receiver, and

$$n(t) = \sum_{l=2}^{N_u} s_{rec}^{(l)}(t) + \tilde{n}(t) \quad (21)$$

is the total interference. The summation term of (21) is the multiple access interference (MAI) due to other users in the system and the second term is the interference due to the channel noise.

3.2 Model for correlator outputs

Assuming that the value of τ_1 is perfectly estimated, the components of the observation vector $\mathbf{r} = (r_{01}, r_{02}, r_{11}, r_{12}, \cdots, r_{(N_s-1)1}, r_{(N_s-1)2})$ are obtained through demodulation process as follows: for $k = 0, 1, \cdots, N_s - 1$,

$$r_{k1} = \int_{kT_f + c_k^{(1)} T_c + \tau_1}^{kT_f + c_k^{(1)} T_c + \tau_1 + T_c} r(t) \cdot q(t - kT_f - c_k^{(1)} T_c - \tau_1) dt \quad (22)$$

and

$$r_{k2} = \int_{kT_f + c_k^{(1)} T_c + \tau_1}^{kT_f + c_k^{(1)} T_c + \tau_1 + T_c} r(t) \cdot q(t - kT_f - c_k^{(1)} T_c - \frac{T_c}{2} - \tau_1) dt. \quad (23)$$

The detector is now to choose between the two hypotheses

$$H_1 : r_{k1} = \theta + n_{k1} \text{ and } r_{k2} = n_{k2} \quad (24)$$

and

$$H_2 : r_{k1} = n_{k1} \text{ and } r_{k2} = \theta + n_{k2} \quad (25)$$

for $k = 0, 1, \cdots, N_s - 1$. In (24) and (25), H_i represents that $s_i^{(1)}(t)$ is transmitted, $\theta = A_1 \tilde{\theta}$ is the value of the signal strength parameter received, and

$$n_{k1} = \int_{kT_f + c_k^{(1)} T_c + \tau_1}^{kT_f + c_k^{(1)} T_c + \tau_1 + T_c} n(t) \cdot q(t - kT_f - c_k^{(1)} T_c - \tau_1) dt \quad (26)$$

and

$$n_{k2} = \int_{kT_f + c_k^{(1)} T_c + \tau_1}^{kT_f + c_k^{(1)} T_c + \tau_1 + T_c} n(t) \cdot q(t - kT_f - c_k^{(1)} T_c - \frac{T_c}{2} - \tau_1) dt \quad (27)$$

are the interference components for $k = 0, 1, \cdots, N_s - 1$.

In this paper, we model $\{(n_{k1}, n_{k2})\}_{k=0}^{N_s-1}$ as i.i.d. bivariate random vectors: that is, the common pdf of $\underline{n} = (n_{k1}, n_{k2})$ is the BISαS pdf

$$f_{\underline{n}}(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp\{-\gamma(\omega_1^2 + \omega_2^2)^{\alpha/2}\} \cdot \exp\{-i(x\omega_1 + y\omega_2)\} d\omega_1 d\omega_2 \quad (28)$$

defined by the inverse Fourier transform. In (28), $i = \sqrt{-1}$, the dispersion parameter $\gamma > 0$ is related to the spread of the BISαS pdf, and the characteristic exponent α takes on a value in the interval $0 < \alpha \leq 2$. The parameter α is related to the heaviness of the tails of the BISαS pdf, with a smaller value indicating heavier tails. When $0 < \alpha < 2$, the BISαS pdf (28) represents an impulsive or heavy-tailed pdf, while the value $\alpha = 2$ corresponds to an uncorrelated Gaussian pdf. Unfortunately, no closed-form expression exists for the general BISαS pdf, except for the two special cases of $\alpha = 1$ (Cauchy) and $\alpha = 2$ (Gaussian):

$$f_{\underline{n}}(x, y) = \begin{cases} \frac{\gamma}{2\pi(x^2+y^2+\gamma^2)^{3/2}} & \text{for } \alpha = 1, \\ \frac{1}{4\pi\gamma} \exp\{-\frac{x^2+y^2}{4\gamma}\} & \text{for } \alpha = 2. \end{cases} \quad (29)$$

For other values of α, the BISαS pdf can be expressed as power series expressions [7].

3.3 Detector based on the proposed detection criterion

Although the Gaussian assumption may sometimes be inappropriate [8], it has been assumed that $n(t)$ in (21) is Gaussian for simplicity in the analysis in most investigations. The Gaussian assumption corresponds to the case of $\alpha = 2$ in (28) or (29). In this case, the ML criterion results in the Gaussian-optimized detector having the decision region

$$D_1^{ML,G} = \left\{ \mathbf{r} : \sum_{k=0}^{N_s-1} r_{k1} \geq \sum_{k=0}^{N_s-1} r_{k2} \right\} \quad (30)$$

with $D_2^{ML,G}$ obtained similarly.

On the other hand, when the distribution for (n_{k1}, n_{k2}) in (26) and (27) is given by (28) and $\alpha \neq 2$, the Cauchy-optimized detector has primarily been used under the general impulsive circumstances. This is because the lack of closed-form expressions for the general BISαS distributions prohibits the computations of an optimum detector, except for the Gaussian and Cauchy distributions [6]. Using the ML criterion, the decision region $D_i^{ML,C}$ of the Cauchy-optimized ML detector can be obtained as

$$D_1^{ML,C} = \left\{ \mathbf{r} : \prod_{k=0}^{N_s-1} (r_{k1}^2 + (r_{k2} - \theta)^2 + \gamma^2) \geq \prod_{k=0}^{N_s-1} ((r_{k1} - \theta)^2 + r_{k2}^2 + \gamma^2) \right\} \quad (31)$$

with $D_2^{ML,C}$ defined similarly. Clearly, the Cauchy-optimized detector based on (31) should first estimate the values of γ and θ for optimum performance.

If we adopt the proposed detection criterion (10), on the other hand, the estimation of θ becomes unnecessary. Specifically, to apply the proposed detection criterion when

$\alpha = 1$, we begin by getting

$$\left.\frac{\partial}{\partial\theta} p(\mathbf{r}|s_i^{(1)}, \theta)\right|_{\theta=0} = \prod_{k=0}^{N_s-1} \frac{\gamma}{2\pi(r_{k1}^2 + r_{k2}^2 + \gamma^2)^{3/2}} \cdot \sum_{k=0}^{N_s-1} \frac{2r_{ki}}{r_{k1}^2 + r_{k2}^2 + \gamma^2}. \quad (32)$$

Hence, the decision region D_i^P of a the detector using the proposed detection criterion is

$$D_1^P = \left\{ \mathbf{r} : \sum_{k=0}^{N_s-1} \frac{r_{k1}}{r_{k1}^2 + r_{k2}^2 + \gamma^2} \geq \sum_{k=0}^{N_s-1} \frac{r_{k2}}{r_{k1}^2 + r_{k2}^2 + \gamma^2} \right\} \quad (33)$$

with D_2^P similarly defined. Although the parameter γ has still to be estimated, it can be obtained easily by, for example, computing the sample mean and sample variance of independent realizations of the BISαS process [9].

3.4 Numerical results

In this section, we compare the performance of three detectors specified by (30), (31), and (33) via computer simulations in a variety of BISαS interference environment. Since the variance of the symmetric α-stable distribution with $\alpha < 2$ is not defined, the standard SNR becomes meaningless. Instead, a new measure called the geometric SNR (G-SNR) is used [10] to indicate the relative strength between the information-bearing signal and symmetric α-stable process. The G-SNR is defined as

$$\text{G-SNR} = \frac{\theta^2}{2C_g^{-1+2/\alpha}\gamma^{2/\alpha}}, \quad (34)$$

where $C_g = \exp\{\lim_{s\to\infty} \left(\sum_{z=1}^{s} \frac{1}{z} - \ln s\right)\} \simeq 1.78$. Note that for the Gaussian case ($\alpha = 2$) the definition of G-SNR is consistent with that of the standard SNR.

In Figures 1 and 2, we show the performance characteristics of the proposed, Cauchy-optimized, and Gaussian-optimized detectors in the Cauchy and Gaussian interference environments, respectively. It is observed that the performance of the proposed detector is almost the same as that of the Cauchy-optimized detector, which becomes clearer in the region where the G-SNR is close to zero.

As the number N_s of UWB pulses per symbol increases, the performance gap between the Cauchy-optimized and proposed detectors becomes more negligible. Since common UWB systems repeat more than one hundred of UWB pulses per symbol, we can see that the proposed and Cauchy-optimized detectors would result in practically the same performance for a practical value of N_s.

Furthermore, it is observed that when the Cauchy-optimized detector estimates the value of θ inaccurately, its performance is not optimum even in the Cauchy environment: the proposed detector will outperform Cauchy-optimized detector with incorrectly estimated value of θ. The Gaussian-optimized detector is the best in the Gaussian environment, but almost always fails to detect signals in the Cauchy environment however large the value of N_s becomes.

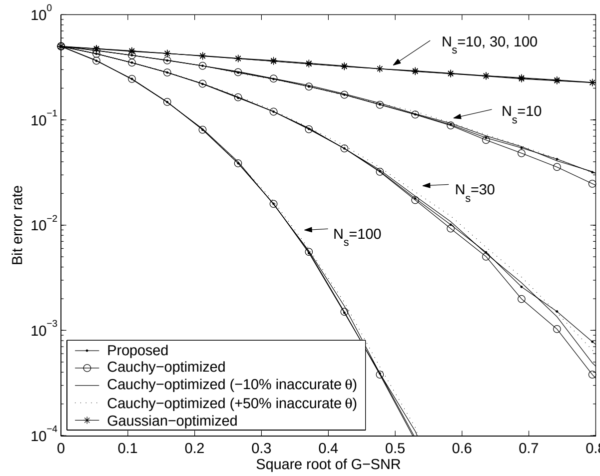

Figure 1. Performance comparison of the proposed, Cauchy-optimized, and Gaussian-optimized detectors in the Cauchy ($\alpha = 1$) environment: the performance of the Cauchy-optimized detectors with θ estimated inaccurately is also included.

In Figure 3, we have shown the bit error rate curves of the three detectors when $N_s = 100$ for several values of the characteristic exponents of the BISαS pdf: $\alpha = 0.5$, $\alpha = 1.3$, and $\alpha = 1.9$. In all the three cases considered, the proposed detector exhibits essentially the same performance as the Cauchy-optimized detector. The proposed detector in addition outperforms the Gaussian-optimized detector for all values of the characteristic exponents considered.

4 Concluding remark

In this paper, we have first proposed a novel detection criterion for weak M-ary signal detection. The proposed detection criterion is designed to be optimum when the signal strength is weak in the sense of minimizing the error probability. In some cases the proposed detection criterion has exactly the same performance as the ML detection criterion. The proposed detection criterion does not require an estimate of the signal strength and consequently results in simpler detector structures.

A new detector based on the proposed detection criterion has then been proposed for the UWB-MA system in the presence of the BISαS impulsive interference. Numerical results demonstrate that the proposed detec-

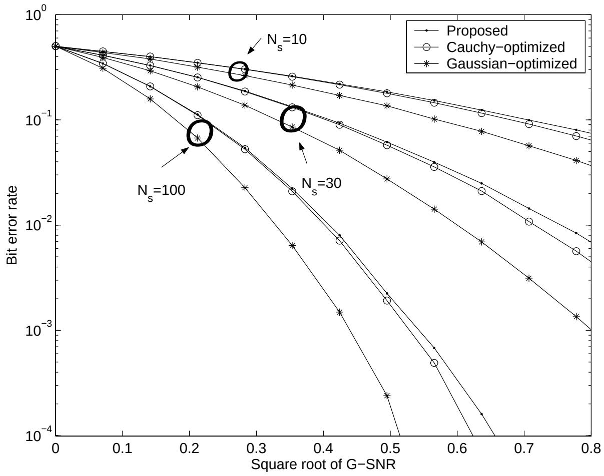

Figure 2. Performance comparison of the proposed, Cauchy-optimized, and Gaussian-optimized detectors in the Gaussian ($\alpha = 2$) environment.

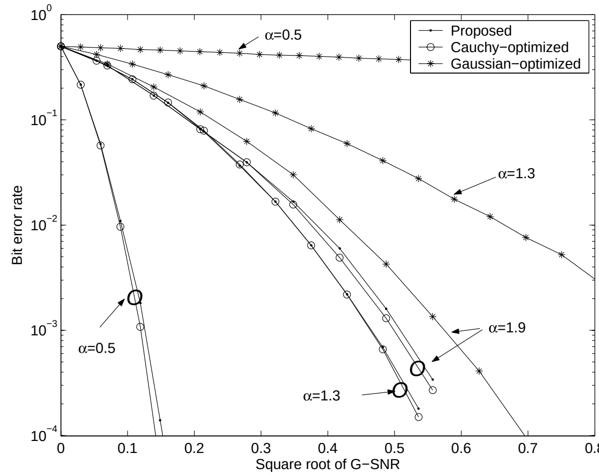

Figure 3. Performance comparison of the proposed, Cauchy-optimized, and Gaussian-optimized detectors with $N_s = 100$ when $\alpha = 0.5$, $\alpha = 1.3$, and $\alpha = 1.9$

tor possesses about the same performance as the Cauchy-optimized detector, while the proposed detector provides us less complexity and simpler detector structures. It is also observed that the proposed detector outperforms the Gaussian-optimized detector in the class of the BISαS impulsive interference.

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