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RADAR WITH RANDOM VARIATION OF PROBING SIGNAL PARAMETERS

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This paper utilizes game-theoretic principles in detecting of Gaussian signals against background of Gaussian noise. We propose the payoff function generalizing signal-to-noise ratio to casual signals. It is found that potential immunity of radar to electronic countermeasure strategies is only achievable through random variation in parameters of sounding signals. Performance limits of radar depend on the product of probing signal bandwidth and its duration. The coherent integration time is to be 2-10 times less than full processing time of the received signal.

Keywords: jammer, radar, game theory, signal.

1. INTRODUCTION

Statistical Hypothesis Testing theory provides a basis for procedures of synthesis of optimum detection algorithms [1,2], the theory gives a principal opportunity to work out optimum detection algorithms for any kind of jamming, irrespective of whether detailed statistical characteristics of signals and jamming are known, or whether under a priori uncertainty conditions [3, 4].

As current methods of algorithm synthesis use a model of signal environment allowing the only active party, that is a radar, the theory is not applicable to synthesis of detection algorithms, if electromagnetic countermeasures (ECM) are employed. When there are electromagnetic countermeasures then there are at least two active parties, a radar trying to improve signal detection and countermeasure systems trying to prevent a radar from operating as well as it might.

Although there isn't an appropriate theoretical framework experts have proposed anti-jam techniques. Note that these techniques don't follow from solution of any classical synthesis problem. For example, there are random changing in signal-carrier frequency, changing of pulse recurrence interval, changing of signal waveform etc. Most every modern radars deploy random variation in parameters of sounding signals against active jamming. Modern communication systems also use random variation in parameters of sounding signals (a.k.a. frequency hopping) to improve noise immunity. Although these anti-jam techniques have proved to be practical, developing of new methods of synthesis and guaranteed immunity resistance to jamming still attract great interest.

The theory of algorithms synthesis for detecting signals in electronic countermeasures based on the model of a game between a radar and jammer can help to meet these goals. [5,6,7,8,9,10].

2. GAME-THEORETIC MODEL OF GAUSSIAN SIGNALS DETECTION

A game-theoretical model consists of two players at least, in our case these are a target and a radar, with the target always trying to prevent the radar from fulfilling its task. Since there are two players and the target and the radar form an adversarial system, their interaction is modelled as a two-person zero-sum game, a.k.a. antagonistic game. On the first stage needed to choose a function of advantage of game.

For example we have an interaction between a radar and a target, where the former tries to locate the target in any kind of bin. The radar operates with variation in parameters of sounding signals and algorithm of processing of the received signals. The target, which carries jamming equipment, tries to generate jamming that could confuse the radar. Thus, this interaction can be represented as a two-person zero-sum game.

We assume that:

player 1 (radar) has a set of **X** possible actions to choose from (pure strategies);

player 2 (jammer) has a set of **Y** pure strategies to pick from;

stands for payoff function for player 1: $H: X \times Y \to R$ (This is criterion for detection efficiency).

The payoff function is critical to choose. On the one hand the payoff function is one of the ECM-resistance properties and on the other hand it is supposed to allow the game to have the solution and nontrivial results.

The quality of detection is normally expressed as the probability of detection for a given conditional probability of false alarm (Neumann-Pearson criterion). Since Neumann-Pearson criterion is a special case of more general average risk criterion the game was formalized and solved, where average risk is the payoff function [1].

The solution of the game shows that the most unfavourable jammer is to come from the detectable signal [5]. Multivariate density of probability of the most unfavourable jammer is expressed as multivariate density of probability of the detectable signal:

$$W_y(\mathrm{x}) = (1-\lambda)\sum_{k=0}^{\infty}\lambda^k W_s^{(k)}(\mathrm{x}) . \qquad (1)$$

Where $\lambda < 1$ reciprocal to comparison threshold of likelihood ratio of Bayes optimal algorithm:

$$\frac{W_s(\mathrm{x})\otimes W_y(\mathrm{x})\otimes W_n(\mathrm{x})}{W_y(\mathrm{x})\otimes W_n(\mathrm{x})} \gtrless \frac{1}{\lambda},$$

$$W_s^{(k)}(\mathrm{x}) = \underbrace{W_s(\mathrm{x})\otimes W_s(\mathrm{x})\otimes\cdots\otimes W_s(\mathrm{x})}_{k}$$

denote convolution of k of probability density $W_s(\mathrm{x})$ of the detectable signal; $W_n(\mathrm{x})$ probability density function of noise.

Correlation function of this kind of jammer and correlation function of the suppressed signal agree within constant multiplier. When the jammer tries to mask Gaussian signal, the radar gets multi-component Gaussian distribution.

Let us compare characteristics of a finite-state masking jammer and characteristics of Gaussian masking jammer with the equal power when Gaussian signal is suppressed (Fig. 1). The diagram shoes that the lines of these two types of jammers are almost coincide. This lets us make a feasible conclusion that the most unfavourable jammers are to be found the range of Gaussian noise.

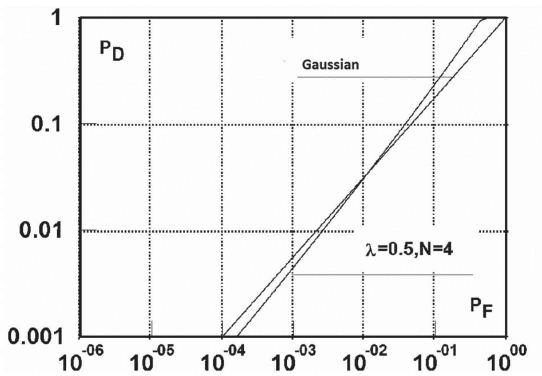

Fig. 1. The performance of detection

We assume that the radar system in operation can use signals of some set: $\mathrm{S}_1 = \{s_1(t;\mathrm{a}) : \mathrm{a} \in \mathrm{A}\}$ with that the received signals are random and can be presented as a model of a Gaussian process. Correlation function of the signal reflected from the target $K_s(t,u;\mathrm{a})$ depends on parameters chosen by the radar. For example, these parameters can be carrier frequency, code phase modulation or some other signal parameters. In this case the received signals belong to the set:

$$\mathrm{S} = \left\{ s(t;\mathrm{a}) : \int_0^T K_s(t,t;\mathrm{a})dt = E_s,\ \mathrm{a} \in \mathrm{A} \right\}, \qquad (2)$$

which we denote as the set of detectable signals

Where: E_s denote average energy of the received signal in a time T; **a** stands for the n-dimensional vector of non-power controlled signal parameters; **A** stands for the set of possible values of signal parameters; s(t,**a**) stands for complex random Gaussian process with zero mean and correlation function $K_S(t,u;\mathbf{a})$.

Assume that a choice of any of the signal parameters $\mathrm{a} \in A$ in (2) and of algorithm for its processing is a strategy for the radar.

The strategy for the jammer is the ability to generate any Gaussian jammer with zero mean and finite mean energy E_n in a time T. Since Gaussian process is completely determined by its mean and the correlation function, the strategy for the jammer is to choose any of the jammer correlation function from the set: $K_n(t,u)$

$$\left\{ K_n(t,u) : \int_0^T K_n(t,t)dt \le E_n \right\}.$$

The jammer has pure strategy since if the jammer has mixed strategies (that is selection of the correlation function $K_n(t,u)$ in relation to some probability measure) this generalizes potential interference to multy-Gaussian interference.

In order to determine the payoff function it should be kept in mind that for every round of the game the goal is to locate Gaussian signal $s(t;\mathrm{a})$ (with parameter $\mathrm{a} \in A$, which is known to the receiving end) against the background of Gaussian jammer with correlation function $K_n(t,u)$ and white Gaussian noise with spectral density $N_0/2$.

It is common knowledge that against background of white noise and Gaussian jammer with correlation function $K_n(t,u)$ optimum Gaussian detector with correlation function $K_s(t,u;\mathrm{a})$ calculates statistics for L(**x**) and compares it with threshold **c** [2]:

$$L(\mathrm{x}) = \sum_k \frac{\alpha_k}{1+\alpha_k} \left| \int_0^T x(t)\phi_k^*(t)dt \right|^2 \gtrless c. \qquad (3)$$

Where: x(t) stands for realization of the detectable signal; α_k and $\phi_k(t)$ denote eigenvalues and eigenfunctions of the integral equation:

$$\int_0^T K_s(t,u;\mathrm{a})\phi_k(u)du = \alpha_k \int_0^T K_\Sigma(t,u)\phi_k(u)du, \qquad (4)$$

$\phi_k(t)$ which incorporates the complex conjugate function $\phi_k(t)$. The eigenfunctions are normalized with the condition:

$$\int_0^T\int_0^T K_\Sigma(t,u)\phi_k(u)\phi_k^*(t)dudt = 1,$$

where $K_\Sigma(t,u) = K_n(t,u) + \frac{N_0}{2}\delta(t-u)$.

Keep in mind that the eigenvalues and eigenfunctions of the integral equation (4) are equal to the eigenvalues and eigenfunctions of the integral operator. $\mathrm{K}_\Sigma^{-1}\mathrm{K}_s$. Where K_Σ denotes the integral operator whose kernel is equal to the sum of correlation function of the signal $K_n(t,u)$ and the correlation function of the interference of white noise: $\frac{N_0}{2}\delta(t-u)$, K_s denotes the integral operator whose kernel is equal to the correlation function of the signal $K_s(t,u;\mathrm{a})$; K_Σ^{-1} stands for the operator which the converse of K_Σ.

Account for x (t) stands for complex Gaussian process for both hypotheses we define the characteristic function of L(x) with no signal (hypothesis H0) and having the signal (hypothesis H1) as:

$$\Theta(v/H_0) = \prod_k \left(1 - \iota v \frac{\alpha_k}{1+\alpha_k}\right)^{-1}, \qquad (5)$$
$$\Theta(v/H_1) = \prod_k \left(1 - \iota v \alpha_k\right)^{-1}$$

(ι denotes imaginary unit)

In relation to the expression (3) infinite number of channels is required for realization of optimal algorithm. If the channels are restricted to some finite number then performance calculation for detection parameters is based on the characteristic functions with finite number of multipliers (5) and the probability calculation of false and successful detection based on these formulas can make use of the technique proposed here: [11].

As it follows from (5) detection characteristics are completely determined by distribution of the eigenvalues α_k of the integral equation (4). See that α_k is signal-to-noise ratio at the output of the k-th processing channel (symbol ξ_k in Fig. 2).

Then we define $\sum_k \alpha_k$ as the total signal-to-noise ratio on all channels of processing. The higher this value is, the better is detection and vice versa.

This gives us the reason to propose the sum of eigenvalues of the operator as the payoff function $K_\Sigma^{-1}K_s$ (the trace of the operator), the payoff function generalizes signal-to-noise ratio to casual Gaussian signals and agrees with signal-to-noise ratio at the output of the linear part of the optimal detector when detecting quasideterministic signals.

Thus we assume the trace of the operator $K_\Sigma^{-1}K_s$ as the payoff function is given as:

$$H(a,K_n)=\int_0^T\int_0^T K_\Sigma^{-1}(t,u)K_s(u,t;\mathrm{a})dudt\,, \qquad (6)$$

where $K_\Sigma^{-1}(t,u)$ stands for the kernel of the integral operator $(K_n+I)^{-1}$, I – for the unity operator.

The electronic countermeasures system tries to reduce (6) by make a selection from the jammers with the correlation function. $K_n(t,u)$ By contrast, the radar tries to find probing-signals $\mathrm{a}\in A$ which are able to increase (6). The processing algorithm (3) remains optimal in the process.

3. GAME SOLUTION AND CONSIDERATION

In the general case game with the payoff function (6) hasn't got a saddle point in pure strategies. We always have:

$$\min_{K_n}\max_a H(a,K_n) > \max_a \min_{K_n} H(a,K_n)$$

Specifically, this means that if the parameters of the detectable signal are known to the jammer, then there exists the Gaussian jammer with the correlation function to make the smallest signal-to-noise ratio at the output of the linear part of the receiver.

This game has a saddle point in mixed strategies. Under given conditions, only player 1 (radar) has the mixed strategy, and pure strategy is always the optimal one for player 2 (jammer).

The payoff function in mixed strategies is given as:

$$H(\mu_a,K_n)=\int_0^T\int_0^T K_\Sigma^{-1}(t,u)K_s(u,t)dudt\,,$$

where: $K_s(t,u)=\int_A K_s(t,u;\mathrm{a})d\mu_\mathrm{a}$, μ_a stands for probability measure defined on the set **A**. This is mixed strategy of the radar. The correlation function $K_s(t,u)$ we shall call the correlation function of the set of detectable signals.

Subject to the limitation (2) the correlation function $K_s(t,u)$ can be expanded to series of eigenfunctions

$$K_s(t,u)=E_s\sum_k \gamma_k\psi_k(t)\psi_k^*(u)\,,$$

where $\sum_k \gamma_k=1$.

The minimum value $H(\mu_a,K_n)$ is achieved when the jammer's correlation function can be expanded by the same system of eigenfunctions

$$K_n(t,u)=\sum_k \lambda_k\psi_k(t)\psi_k^*(u),\quad \sum_k\lambda_k\le E_n\,. \qquad (7)$$

where:

$$H(\mu_a,K_n)=E_s\sum_k\frac{\gamma_k}{\lambda_k+N_0/2}\,. \qquad (8)$$

Minimizing (8) λ_k subject to the limitation $\sum_k\lambda_k\le E_n$, $\lambda_k\ge 0$ we obtain

$$\lambda_k^0=\begin{cases}\left(E_n+m\dfrac{N_0}{2}\right)\dfrac{\gamma_k^{1/2}}{\sum_{i=1}^m\gamma_i^{1/2}}-\dfrac{N_0}{2},\ k\le m\\ 0,\ k>m.\end{cases} \qquad (9)$$

The eigenvalues γ_k are in descending order of their values, m stands for the largest integer for which the inequality $\lambda_m^0>0$ is true, viz $\gamma_m^{1/2}>\sum_{k=1}^m\gamma_k^{1/2}\Big/\left(\dfrac{2E_n}{N_0}+m\right)$.

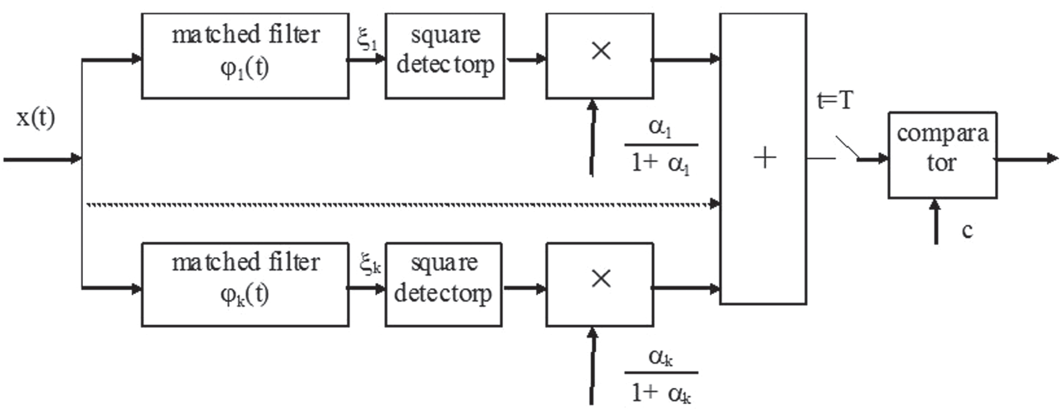

Fig. 2. Optimal detector diagram

Account for (7) and (9) we shall get that the correlation function of the jammer is given as the finite series:

$$K_n^0(t,u)=\sum_{k=1}^{m}\lambda_k^0\psi_k(t)\psi_k^*(u),$$

and the price of the game is:

$$H(\mu_a^0,K_n^0)=\frac{E_s}{E_n+mN_0/2}\left(\sum_{k=1}^{m}\sqrt{\gamma_k}\right)^2+$$

$$+\frac{2E_s}{N_0}\left(1-\sum_{k=1}^{m}\gamma_k\right).$$

The expression for the correlation function of the worst-case jammer agrees with the similar expression which was proposed in [6], where the game-theoretic was used assuming that the signal is known. It implies that optimal strategy for the jammer doesn't depend on the type of signals randomness, whether it is determined by radar, whether it is determined by the medium or both.

In many cases the signal is random due to multiplicative noise, and the correlation function is given as:

$$K_s(t,u;\mathrm{a})=E_s\rho(t,u)s(t,\mathrm{a})s^*(u,\mathrm{a}),$$

where $\rho(t,u)$ stands for the correlation function of the fluctuation of the complex envelope of the detectable signal, which is independent from **a**; $s(t,\mathrm{a})$ denotes the final complex function; $s^*(t,\mathrm{a})$ denotes complex conjugate function $s(t,\mathrm{a})$.

It is found in [7] that if controlled parameters of the signal $\mathrm{a}\in A$ are nonpower kind then selection of this parameter with equal probability is the optimal mixed strategy for the radar.

In this case the eigenvalues and the eigenfunctions of the integral equation (4) are given as:

$$\alpha_k=\begin{cases}\frac{E_s}{q}\nu_k^{1/2}\sum_{j\in J}\beta_j^{1/2}+\frac{2E_s\nu_k}{N_0}\left(1-\sum_{j\in J}\beta_j\right), & k\in I,\\ \frac{2E_s}{N_0}\nu_k, & k\notin I.\end{cases}\quad(10)$$

$$\phi_k(t)=\begin{cases}\psi_k(t)h(t;a), & k\in I,\\ \psi_k(t)s(t;a), & k\notin I.\end{cases}$$

Where ν_k and $\psi_k(t)$ denote the eigenvalues and the eigenfunctions of the correlation function of the fluctuations; $\rho(t,u)$, β_k and $f_k(t)$ stand for the eigenvalues and the eigenfunctions of the correlation function. $\int_A s(t,\mathrm{a})s^*(u,\mathrm{a})d\mu_{\mathrm{a}}$.

Arrange the outcomes of eigenvalues $\nu_i\beta_j$ in decreasing order and give then numbers 1,2, .., k, in such a way, that $\nu_{i_k}\beta_{j_k}$ will be the k-th member of the sequence.

Then

$$q=\frac{E_n+m\frac{N_0}{2}}{\sum_{k=1}^{m}\nu_{i_k}^{1/2}\beta_{j_k}^{1/2}},\quad I=\{i_1,i_2,\ldots,i_m\},\ J=\{j_1,j_2,\ldots,j_m\},$$

m stands for the largest integer for which the inequality

$$\nu_{i_m}^{1/2}\beta_{j_m}^{1/2}>\sum_{k=1}^{m}\nu_{i_k}^{1/2}\beta_{j_k}^{1/2}\Big/\left(\frac{2E_n}{N_0}+m\right).$$

is true: Function h(t;**a**) agrees with:

$$h(t;\mathrm{a})=s(t;\mathrm{a})-\sum_{j\in J}\left(1-\frac{N_0}{2q\beta_j^{1/2}}\right)s_j(\mathrm{a})f_j(t).$$

See that this is the weight of the optimal detector of deterministic signals s(t;**a**) with random variation of parameter $\mathrm{a}\in A$ against background of worst-case Gaussian noise [8].

Hence the algorithm for the optimal detector of random Gaussian signals against background of worst-case Gaussian noise is as given:

$$L(x)=\sum_{k\in I}\frac{\alpha_k}{1+\alpha_k}\left|\int_0^T x(t)\psi_k^*(t)h^*(t;\mathrm{a})dt\right|^2+$$

$$+\sum_{k\notin I}\frac{2E_s\nu_k/N_0}{1+2E_s\nu_k/N_0}\left|\int_0^T x(t)\psi_k^*(t)s^*(t;\mathrm{a})dt\right|^2>c.\quad(11)$$

With a view to simplification of the algorithm the second item of the sum (11) can be omitted. This is tantamount to eliminating of the lower line in the brace in the expression (10) The technique proposed in [9] allows developing corresponding performance characteristics. In case of long-term fluctuations when the eigenvalues of α_k don't agree the formulas for probabilities of false alarm and successful detection are as given:

Successful detection:

$$P_D=1-\sum_{i\in I}\frac{1-\exp(-c/\alpha_i)}{\prod_{j\neq i,j\in I}\left(1-\frac{\alpha_j}{\alpha_i}\right)}.$$

False alarm probability:

$$P_F=\prod_{i\in I}(1+\alpha_i)\sum_{i\in I}\frac{\exp(-c\cdot(1+\alpha_i)/\alpha_i)}{(1+\alpha_i)\prod_{j\neq i,j\in I}(1-\frac{\alpha_j}{\alpha_i})}.$$

Where c denotes the relative detection threshold

4. POTENTIAL NOISE-IMMUNITY OF RADAR WITH A RANDOM VARIATION OF THE PROBING SIGNALS

We ask, not whether there is an optimal type of signal which provides the highest of radar noise-immunity?

To search for such signals, it is desirable not to limit their set parametric representation, and enter only significant limitations, implementation of which necessarily from physical considerations.

Such restrictions can be considered a frequency band in which the radar can operate, the time of coherent and incoherent accumulation.

Signals received by the radar are random due to fluctuations the reflecting surface of the target.

These fluctuations are multiplicative noise:

$$s(t,a) = \xi(t) s_s(t,a),$$

where $\xi(t)$ — Gaussian random process; $s_s(t,a)$ — probe signal; $\xi(t)$ varies slowly compared to $s_s(t,a)$.

We approximate the multiplicative interference by sequence pulse (Figure 3):

$$\xi(t) = \sum_i \xi_i \quad (t - iT_0), \quad (t) = \begin{cases} 1, \ t \in [0, T_0] \\ 0, \ t \notin [0, T_0] \end{cases}.$$

Then

$$s(t,a) = \sum_i \xi_i s_i (t - iT_0, a_i).$$

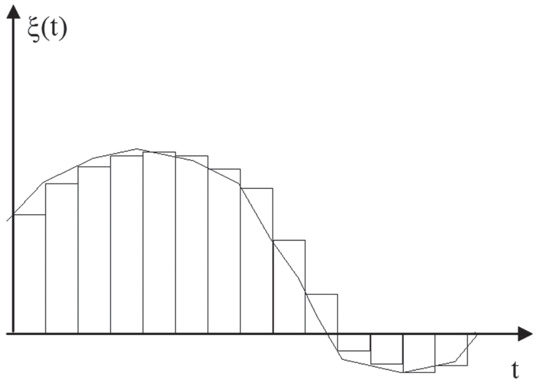

Fig. 3

It is known that the signal can be represented as a series of orthogonal functions. These functions are eigenfunctions of the integral equation:

$$\int_0^{T_0} \frac{\sin(2\pi\Delta f(t-u))}{2\pi\Delta f(t-u)} \phi_i(u) du = \lambda_i \phi_i(t), \ t \in [0, T_0]$$

and are called circular spheroidal. They have a greater concentration of the spectrum in the band Δf.

As shown in [10] is enough to choose the length of the series $n = [\Delta f T]$ ([x] – integer part of x).

Thus, the set of probing signals of duration T and the width of the spectrum Δf is of the form of:

$$S = \left\{ s(t,a) : s(t,a) = \sum_{i=0}^{N-1} \sum_{k=0}^{n-1} a_{ik} \Psi_k (t - iT_0) \right\}.$$

Here a_{ik} – the parameters selected on the side of the radar.

In [10] is shown that, the parameters are selected independently for each piece of the signal in the time interval $[iT_0, (i+1)T_0]$.

The parameters are selected inside track equally likely from ensemble: $\left\{ a : \sum_{i=0}^{N-1} |a_i|^2 = 1 \right\}$.

Parameter detection α_k can be written as:

$$\alpha_k = \frac{P_s}{P_n + \frac{\Delta f N_0}{2}} \Delta f T \nu_k. \quad (10)$$

Here P_s is the signal power, P_n is the jammer power, ν_k – the eigenvalues of the correlation matrix of sequence ξ_i.

Detection characteristics depend only on the multiplicative noise and on the product width of the spectrum of signals on duration. The parameters of the partition into intervals of duration T0 only affect the precision of the multiplicative noise.

Equation (10) determines the optimal noise immunity of radar when using continuous signals. If you are using pulsed signals, parameter of the detect will take type:

$$\alpha_k = \frac{P_s}{P_n + \frac{\Delta f N_0}{2}} \Delta f T \frac{\tau}{T_n} \nu_k.$$

Here $\frac{T_n}{\tau}$ – pulse on-off time ratio.

Thus, the potential noise immunity of a pulsed radar inversely proportional to the pulse on-off time ratio.

It is consider the case when the observation time can be divided into n non-overlapping intervals. In each interval can be a coherent accumulation, and fluctuations in the adjacent intervals between themselves independent. If the duration of coherent accumulation is *Tkog* then $n = T / T_{kog}$.

In this case $\alpha_k = d^2 = d_0^2 \frac{1}{n}$.

Working feature of detection is easily determined in terms of the chi-square distribution with 2n degrees of freedom: $F(x;2N) = \int_0^x \frac{t^{N-1}}{2^N (N-1)!} e^{-t/2} dt$:

$$P_D = 1 - F\left(\frac{F^{-1}(1 - P_F; 2n)}{1 + d^2}; 2n \right).$$

Here P_d – detection probability; P_F – false alarm, $F^{-1}(x;2n)$ – the inverse $F(x;2n)$.

The value of parameter detection d_0^2, required to provide a given probability of correct detection and false alarm can be obtained from the expression:

$$d_0^2 = \left(\frac{F^{-1}(1 - P_F; 2n)}{F^{-1}(1 - P_D; 2n)} - 1 \right) n.$$

On Fig. 4 shows the parameter detection d_0^2 on the ratio between the total accumulation time and time coherent integration n for the probability of false alarm P_F = 10-8.

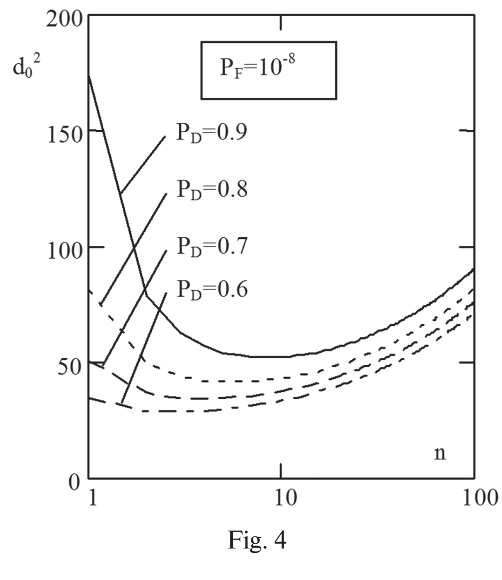

Fig. 4

From the figures it is clear that for a fixed probability of false alarm, there is an optimal ratio between the total accumulation time and time coherent integration n, which requires minimum value detection d_0^2 to provide the required detection probability. This optimum is the more pronounced the greater the required probability of correct detection.

On the other hand the optimum is not sharp and close to optimal values are obtained in the range. $2 \le n \le 10$.

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Rodionov Vladimir Valentinovich, for photograph and biography, see this issue, p. 98.

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В статье рассмотрено обнаружение гауссовых сигналов на фоне гауссова шума с использованием принципов теории игр. Предложена функция компенсации, обобщающая отношение сигнал-шум на случайные сигналы. Показано, что потенциальная устойчивость радара к стратегиям радиоэлектронного противодействия достижима только при случайном изменении параметров зондирующего сигнала. Потенциальные возможности радара определяются произведением полосы частот и длительности зондирующего сигнала. Время когерентного накопления должно быть в 2–10 раз меньше полного времени обработки принятого сигнала.

Ключевые слова: постановщик помех, радар, теория игр, сигнал.

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У статті розглянуто виявлення гаусових сигналів на тлі гаусової перешкоди за використання принципів теорії ігор. Запропоновано функцію компенсації, що узагальнює відношення сигнал-шум на випадкові сигнали. Показано, що потенційна опірність радару до стратегій радіоелектронної протидії досяжна тільки за випадкової зміни параметрів зондуючого сигналу. Потенційні можливості радара визначаються добутком смуги частот і тривалості зондуючого сигналу. Термін когерентного накопичення має бути в 2–10 разів менший від повного часу обробки прийнятого сигналу.

Ключові слова: постановник завад, радар, теорія ігор, сигнал.

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