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Algorithm for adaptive energy-cyclostationary detection of noise-like signals

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Abstract. Contemporary radio communication systems and assets operate in a complex radioelectronic environment. These systems and assets are integrated into a single network by means of digital radio communications means, which are increasingly using noise-like signals to transmit information. In conditions of constant monitoring by radio frequency spectrum analysis assets and radiation source direction finding in the conduct of hostilities, the need to ensure the covert control of forces and assets remains relevant. Thus, the forces and assets' task of detecting, analysing, direction finding and further controlling the covert radio communication systems' detected signals is no less relevant. The object's problem, which is partially addressed in this research, is the need to increase the probability that noise-like signals can be correctly detected on the background of additive white Gaussian noise by modern automated detection and analysis assets. The article is aimed at improving the algorithm for detecting noise-like signals by using an adaptive energy-cyclostationary detection device. The article reviews the known methods of radio detection and compares their effectiveness in detecting and analysing the noise-like signals parameters on the white Gaussian additive noise background. The effectiveness issues of using an adaptive energy-cyclostationary device for detecting noise-like signals in radio communication systems are researched. The study results and the operation algorithm of the proposed detection device, which combines the energy and cyclostationary detection methods' properties, allow increasing the probability of detecting noise-like signals at lower signal-to-noise ratios values.

Keywords: radio communication systems, noise-like signal, algorithm, correct detection probability, Gaussian noise, energy detection device, cyclostationary detection device.

Introduction

In the armed forces of many countries, information support for commanders is performed by using automated command and control systems (Masnoy, Sudakov, 2003). These systems are connected into a single network by digital radio communications assets using noise-like signals (NLS) (Chaika, 2004). The noise-like signals have the high energy concealment property from radio technical intelligence (RTI), which allows the radio communication system (RCS) to function effectively at very small signal-to-noise ratio's (SNR) values at the receiver input (up to -30 dB) (Borisov, Zinchuk, Lymarev et al., 2003).

Today, the problem of radio technical assets (RTAs) effective jamming is solved by generating interference based on a posteriori information about the parameters of their radio signals. The receivers used to detect and estimate the parameters of RTA's radio signals do not provide high-quality tasks fulfilment when receiving the NLS. Therefore, the NLS detection task remains not completely solved.

Literature review

To devices that provide NLS detection, the following types can be attributed: energy (Varakin, 1985; Poisel, 2008; Kay, 1998; Fishman, 1992; Urkowitz, 1967), detection using a matched filter (Kay, 1998;

Torrieri, 2005), cyclostationary (Napolitano, 2012; Gardner, Spooner, 1992; Gardner, Zivanovic, 1991; Dandawate, Giannakis, 1994), detection using eigenvalues (Zeng, Liang, 2009; Penna, Garello, Spirito, 2009; Cardoso, Debbah, Bianchi, Najim, 2008), detection based on wavelet transforms (Khmelev, Trushkov, 2014), covariance detection methods (Zeng, Liang, 2009). The last four methods' groups are quite effective at small signal-to-noise ratio (SNR) values, but require complex calculations. When solving electronic warfare (EW) tasks, the time spent on detecting and analysing the parameters of radio signals, including NLS, should be minimal (Perunov, Fomichev, Yudin, 2003).

Therefore, the task of developing (improving) methods for detecting and estimating the noise-like signal parameters that ensure prompt decision-making at low SNR values in the EW interests remains relevant.

Materials and Methods

For the NLS detection in the EW's interests, it is most appropriate to use an energy detection device (Perunov, Fomichev, Yudin, 2003; Torrieri, 2005). This is a relatively simple detection method, but requires precise information about the noise power spectral density to determine the detection threshold. Moreover, an incorrect estimate leads to errors in decision-making (Fishman, 1992).

Cyclostationary detection is an alternative detection method because communication signals are cyclostationary and noise is stationary (Napolitano, 2012). The cyclostationary method's advantage is the ability to operate without a priori information about N_0 and detect signals at small SNR values. However, one major disadvantage of cyclostationary detection methods is the large amount of calculations.

Taking into account the operation limitations of the energy detection device (a priori information about N_0), the idea of this article is to synthesise such a device that is invariant to N_0, by combining a cyclostationary detection device and an energy detection device with a doubling frequency.

Let us assume that the NLS detection $s(t)$ occurs on the white Gaussian noise background $n(t)$ with power spectral density N_0.

The energy detection device's (radiometer) schematic diagram is shown in Fig. 1. The band-pass filter has a central frequency $f_{c\phi}$ and a bandwidth $W_{c\phi}$. Behind it is placed a quadratic device, the voltage from the output of which goes to the integrator and then to the threshold device input, where it is compared with the pre-set energy threshold ξ_0. At the threshold device's output with the analysis interval T_a, a decision is made.

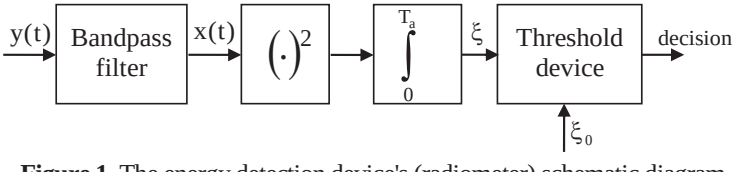


Figure 1. The energy detection device's (radiometer) schematic diagram

On the integrator output, the following magnitude is formed (Varakin, 1985)

$$\xi = \frac{1}{T_a}\int_0^{T_a} x^2(t)dt\,, \tag{1}$$

where $x(t)$ – fluctuations at the output of the radiometer bandpass filter.

The threshold device compares the magnitude ξ with a certain constant ξ_0, which is a function from the desired level of false alarm probability.

Let's consider two hypotheses: H_0 – the radiometer's input receives only noise $n(t)$ and H_1 the radiometer's input receives an additive signal $s(t)$ and noise $n(t)$ combination. At a small SNR, which is quite common in practice, a long analysis time is required for reliable detection. he probability density function of the radiometer output statistics at $W_{сф}T_a >> 1$ approximated by a Gaussian law, then for both hypotheses the expressions for the mathematical expectation μ and variance σ of the signal energy estimate are (Torrieri, 2005):

$$\begin{aligned} H_0: \quad & \mu_1 = N_0 \cdot T_a \cdot W_{сф}, & \sigma_1^2 = N_0^2 \cdot T_a \cdot W_{сф}, \\ H_1: \quad & \mu_2 = N_0 \cdot T_a \cdot W_{сф} \cdot (1+\rho), & \sigma_2^2 = N_0^2 \cdot T_a \cdot W_{сф} \cdot (1+2\rho), \end{aligned} \qquad (2)$$

where $\rho = \dfrac{P_c}{W_{сф} \cdot N_0}$ – the signal power ratio to the noise power spectral density in the filter passband; P_c – signal power $x(t)$ for the analysis time T_a.

Radiometer efficiency is characterised by the false alarm probability P_{xm} and the correct detection probability P_B of signal. Expressions for their calculation (Torrieri, 2005):

$$\begin{aligned} P_{xm} &\approx Q\left(\frac{\xi_0 - N_0 \cdot T_a \cdot W_{сф}}{N_0\sqrt{T_a \cdot W_{сф}}}\right), \\ P_B &\approx Q\left(\frac{\xi_0 - N_0 \cdot T_a \cdot W_{сф} \cdot (\rho+1)}{N_0\sqrt{T_a \cdot W_{сф} \cdot (2\rho+1)}}\right), \end{aligned} \qquad (3)$$

where $Q(x) = \dfrac{1}{\sqrt{2\pi}} \int_x^\infty exp\left(-\dfrac{u^2}{2}\right) du$ – generalised Marcum's function (Torrieri, 2005).

To ensure the required values of the false alarm probability P_{xm} it is possible to calculate the radiometer threshold level as an energy detection device (Torrieri, 2005):

$$\xi_0 \approx N_0\left(\sqrt{T_a \cdot W_{сф}} \cdot Q^{-1}(P_{xm}) + T_a \cdot W_{сф}\right), \qquad (4)$$

де $Q^{-1}(\cdot)$ – inverse Marcum's function.

Despite the detailed analysis of the above structural scheme (Fig. 1), its scope is limited, because it is necessary to a priori know the noise power spectral density N_0. Despite the detailed analysis of the above structural scheme (Fig. 1), its scope is limited, because it is necessary to a priori know the noise power spectral density . In the case of performing reconnaissance tasks, as a rule, the SNR real values is also unknown (Borisov, Zinchuk, Lymarev et al., 2003). The noise level estimation brings additional errors, especially during the NLS detection, when other signals may be present in a given frequency range. Besides, the detection threshold cannot be determined exactly, so the radiometer's operating characteristics deteriorate significantly.

Let us compare the radiometer's operationing efficiency and the detection device with frequency doubling (Fig. 2) according to the criterion given in (Poisel, 2008) – the SNR output level, according to which the best detection device is determined by the maximum SNR level on the output.

Let the input of each detection device be a noise-like signal combination with additive white Gaussian noise with one-sided power spectral density N_0. SNR level on the input for both detection devices $\rho_{вх}$ is defined as $\rho_{вх} = E_{імп}/N_0$, where $E_{імп} = P_{імп}\tau_{імп}$ – the pulse energy of NLS code sequence and, as a rule, $\rho_{вх} < 1$.

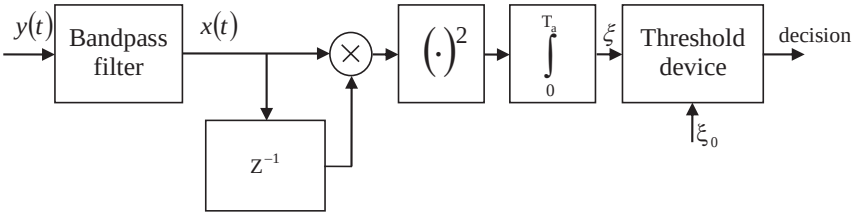


Figure 2. Block diagram of the frequency doubling detection device

The following correlations exist between the SNR input and output values for each detection device (Poisel, 2008):

$$\rho_p = 0.667\, N_{імп}\rho_{вх}^2,$$
$$\rho_{пч} = 0.333\, N_{імп}\rho_{вх}^2, \quad (5)$$

where $N_{імп}$ – code sequence pulses number for the analysis time T_a.

Fig. 3 shows the dependence between the input and output SNR values for the two detection devices considered above at $N_{імп} = 10^6$. As can be seen, the energy detection device has better detection characteristics at all SNR values on the input.

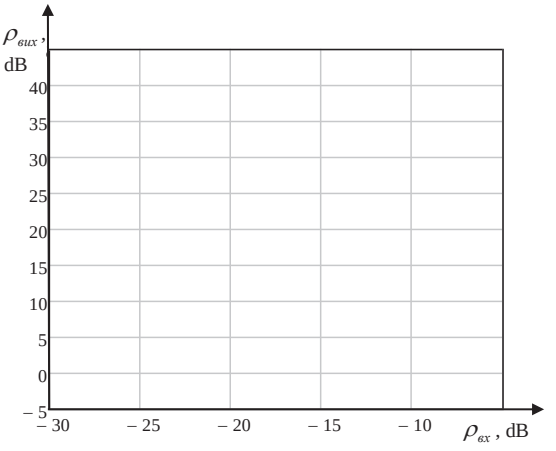


Figure 3. WHS output values dependence graphs versus input values for the radiometer (solid line) and the frequency doubling detection device (dashed line)

Let's conduct a comparative analysis of the detection probability dependence $P_в$ rom the SNR output values. We will use the calculation expressions $P_в$ or a radiometer and a frequency-doubling detection device (Poisel, 2008):

$$P_в^p = \frac{1}{2} erfc\left[erfc^{-1}(2P_{хт}) - \sqrt{\frac{\rho_p}{2}} \right], \quad (6)$$

$$P_в^{пч} = \int_{-ln(P_{хт})}^{\infty} e^{-(z+\rho_{пч})} \cdot I_0(2\sqrt{z \cdot \rho_{пч}})dz,$$

where $erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2)dt$ – additional error integral, I_0 – modified zero-order Bessel function.

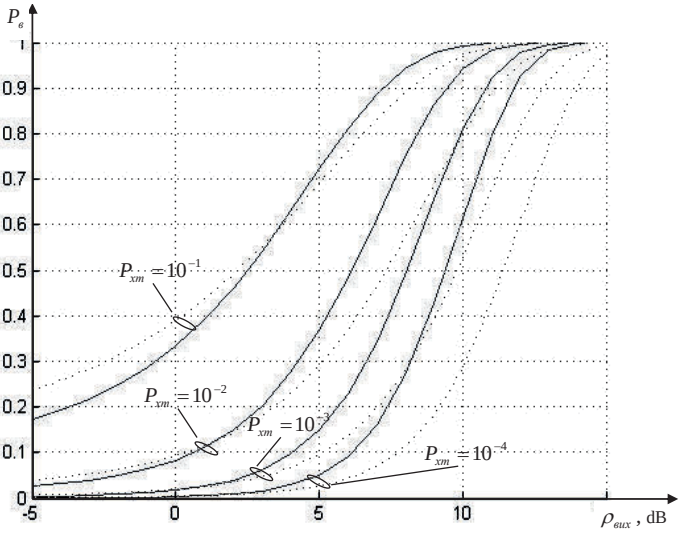


Figure 4. Detection probability dependence graphs $P_в$ versus output SNR values for a radiometer (solid line) and a frequency-doubling detector (dashed line)

As shown in Fig. 4 $P_в^p$ exceeds $P_в^{пч}$ not for all SNR output values. Using the above considerations, it is proposed to combine these two detection devices together and introduce a commutator and an analysis module (Fig. 5), which evaluates the value $P_в^p$ and $P_в^{пч}$ according to expressions (6). The decision-making will be based on those detection device data, the estimated detection probability of which is higher, if the probability of both detection devices is the same, the radiometer is preferred.

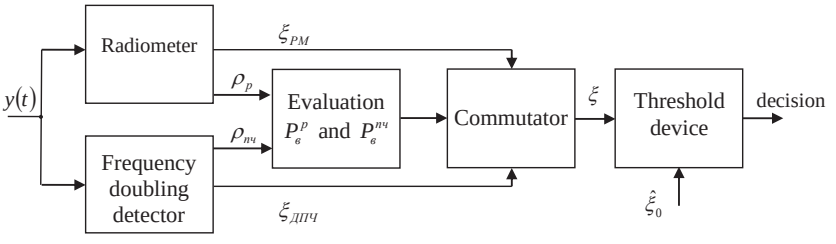


Figure 5. Energy detection device structural diagram

Radiometer operation's analysis in case of errors in assessment N_0 showed that in the case of detection, when the evaluated noise level values $\hat{N}_0$ less than its real indicator N_0, the energy level of the

received signal falls into the interval $[\hat{\xi}_0, \xi_0]$ (fig. 6a). This leads to a hypothesis being accepted H_1 in a signal absence, which increases the false alarm probability.

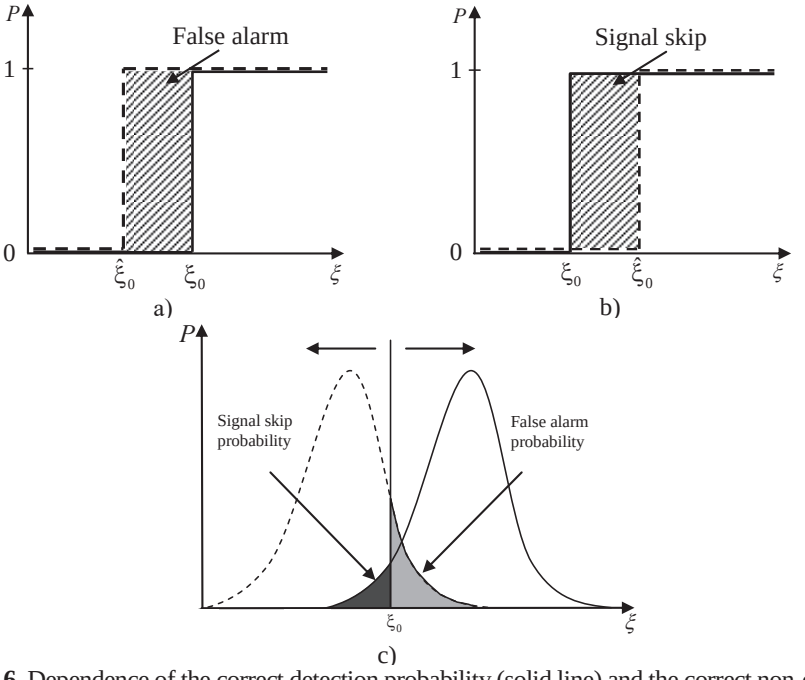


Figure 6. Dependence of the correct detection probability (solid line) and the correct non-detection probability (dashed line) from the threshold threshold values

With $\hat{N}_0 > N_0$ the incorrect decision occurs when the energy level of the received signal falls into the interval $\left[\xi_0, \hat{\xi}_0\right]$ (Fig. 6b). This error leads to the hypothesis acceptance H_0 n case when the signal is present, which increases the probability of skipping the target.

Fig. 7 shows the detection probability dependence graphs from the SNR on the receiver input according to expressions (3) and (4) with $W_{cф} = 1$ MHz, $T_a = 10^{-4}$ s, $P_{xm} = 10^{-3}$ and different estimation error values $\hat{N}_0$.

Thus, the use of noise power spectral density estimation leads to additional errors occurring at the NLS detection. As a consequence, an inaccurately determined detection threshold leads to an incorrect decision-making about the signal presence or absence in the threshold radiometer device.

It is known (Perunov, Fomichev, Yudin, 2003) that to evaluate the cyclostationary signal correlation properties, the autocorrelation function can be used

$$R_x(t,\tau) = \sum_{\alpha} R_x^{\alpha}(\tau) e^{j2\pi\alpha \cdot t}, \tag{7}$$

where $R_x^{\alpha}(\tau)$ – process cyclic autocorrelation function $x(t)$ with cyclic frequency α; τ – observation time interval.

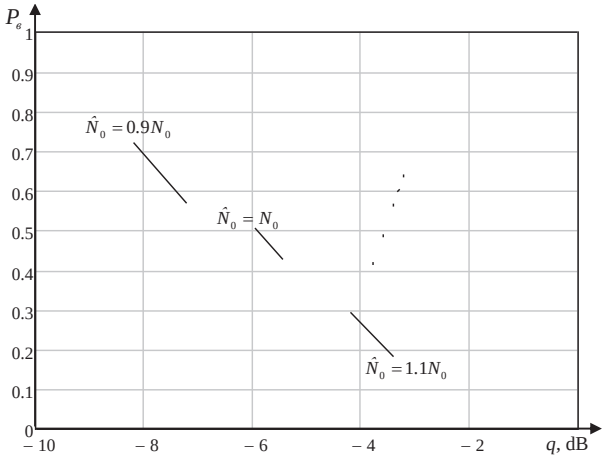


Figure 7. Signal detection probability dependence from SNR under estimation errors N_0

The cyclic autocorrelation function values can be obtained from the expression (Perunov, Fomichev, Yudin, 2003):

$$R_x^{\alpha}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x\left(t+\frac{\tau}{2}\right) \cdot x\left(t-\frac{\tau}{2}\right)^{*} e^{-j2\pi\alpha t} dt, \tag{8}$$

When the cyclostationary model is adapted to the useful signal, the statistical test at multicyclic coherent detection has the following form (Napolitano, 2012):

$$\begin{gathered} \xi = \sum_{\alpha} \frac{1}{N_0^2} \int_{-W_{c\phi}/2}^{W_{c\phi}/2} R_x^{\alpha}(\tau)^{*} R_y^{\alpha}(\tau) d\tau, \\ \xi^{u} < \xi_0^{u} \text{ at } H_0, \\ \xi^{u} > \xi_0^{u} \text{ at } H_1. \end{gathered} \tag{9}$$

where $R_y^{\alpha}(\tau)$ – cyclic autocorrelation function $\mathrm{y(t)}$, ξ^{u} – threshold at the cyclostationary detection method.

Results

Besides the sensitivity to the values N_0, which reduces the detection efficiency at small SNR values, the energy detection device is the best solution for detecting an NLS with unknown parameters. Moreover, this method is very easy to perform. At the same time, cyclostationary detection is quite effective, but requires a significant amount of calculations or a priori information about the cyclic frequency to make a quick decision. This information is unknown, so the detection process becomes too complex and cannot be implemented in real time. However, these two detection methods can supplement each other, which is proposed in this article by creating a hybrid detection device (Fig. 8).

Let us assume that the values N_0 is a time-varying value, ξ – is the received signal energy $x(t)$ during the observation time T_a after i -iteration, $\xi_0 = \infty$ – is the initial values of the hybrid detection device energy threshold.

The adaptive energy-cyclostationary detection operation algorithm for noise-like signals is shown in Fig. 9. The energy detection device calculates the energy ξ of the received signal over time T_a according to (1). If $\xi < \xi_0$ – the energy detection device cannot make an exact decision about the signal presence or

absence. In this case, a test for the received oscillation cyclostationarity is performed $x(t)$. If the signal is not detected, the calculated values ξ^{u} is stored in the array $|\xi|$, from which the variable average μ_1 and according to (2) and (4) calculated $\hat{N}_0$ and $\hat{\xi}_0$. Into the variable ξ_0 is stored (reassigned) the values $\hat{\xi}_0$ and detection process starts from the beginning. The algorithm would end its operation, when $\hat{\xi}_0$ equates ξ_0, i.e. signal $x(t)$ is not detected, and the detection threshold values determined by both detection devices will be identical.

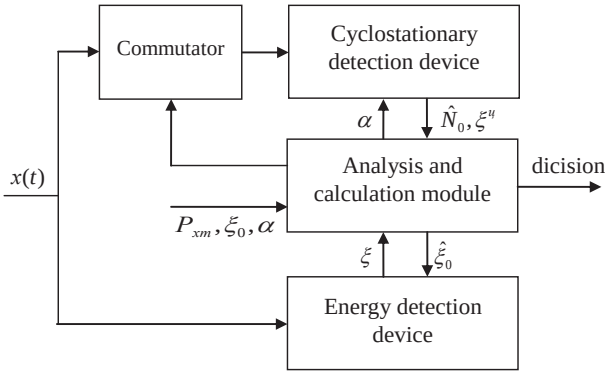


Figure 8. Hybrid detection device schematic diagram.

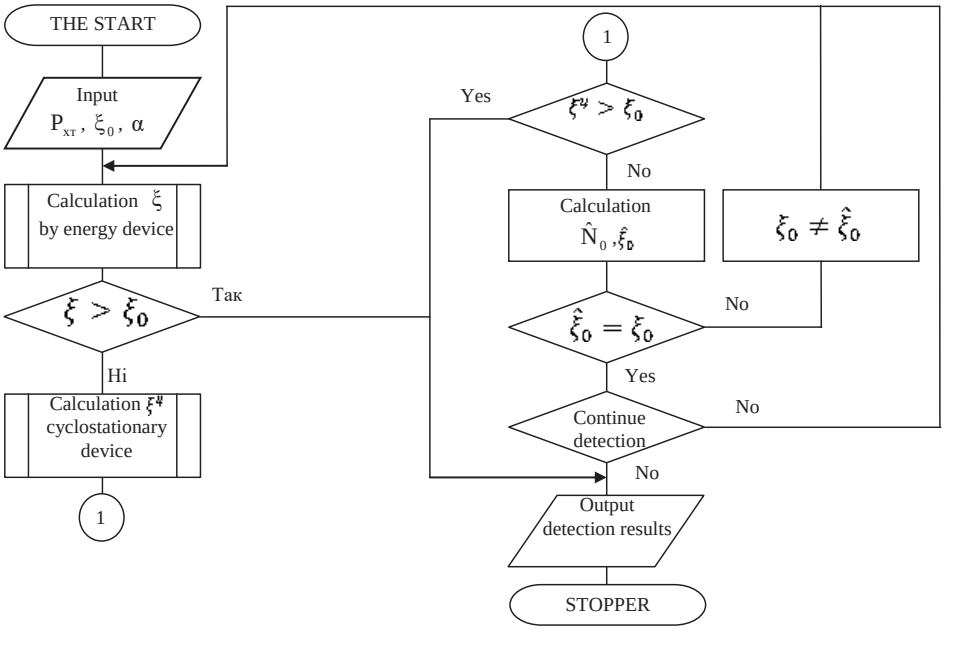


Figure 9. Adaptive energy-cyclostationary noise-like signal detection operating algorithm

As a result of using the proposed algorithm, the number of calculation operations during detection is reduced from $N^2 + 0.5N\,log_2\,N$ (for a cyclostationary detection device at the start of the algorithm operation) till $N\,log_2\,N$ (for a radiometer at the calculated values $\hat{\xi}_0$). Thus, the quality of the proposed hybrid detection device (Fig. 9) approaches the cyclostationary one in quality and has the time for analysis corresponding to the energy detection device.

From the modelling results graphs (Fig. 10), it can be seen that by using the proposed hybrid device, we have a gain in detection probability at SNR smaller values. This gain is achieved by using the detection device with a frequency doubling (as part of the energy detector) of the detection threshold values calculated by the cyclostationary device.

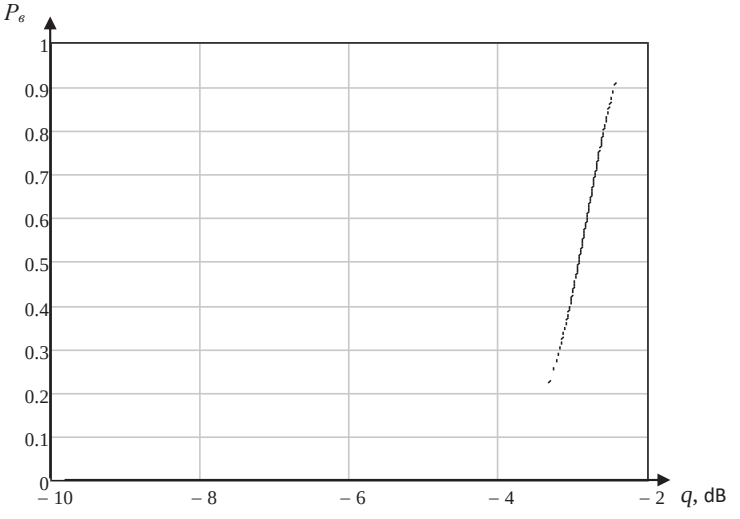


Figure 10. Detection probability dependence versus SNR of the proposed detection device using a detector with frequency doubling (dashed line) and without it (solid line)

Discussions

The prospects for further research may include: specifying the detection conditions for noise-like radio signals with pseudo-random operating frequency tuning and direct spectrum expansion; optimising the mathematical and algorithmic support for the noise-like radio signal detection process; minimising computational costs.

Conclusion

1. The hybrid detection device combines the energy and cyclostationary methods' properties, which ensures an increased probability of noise-like signals correct detection at the time costs corresponding to the energy detection device.

2. Combining two detection devices (a radiometer and a frequency-doubling detection device) into one - an energy one, in which, depending on the SNR at the outputs, a decision is made about the use of one or the other device according to the maximum probability criteria for the correct radio signal detection. The comparison results of the efficiency of their use at an output SNR at different values are presented.

3. The probability dependence of the NLS correct detection on the determination accuracy of the noise power spectral density and the corresponding detection threshold is shown.

4. The use of a cyclostationary detection device as part of a hybrid one provides the possibility of selective refinement of the noise power spectral density and detection threshold.

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