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METHOD OF DETECTION OF DIGITAL RADIO SIGNALS USING DIFFERENTIAL CONVERSION

In industrial intelligence, embedded devices with radio channels, known as radio jamming devices, are commonly used to covertly intercept and transmit information. These devices utilize electromagnetic waves, which can travel long distances undetected, making remote surveillance possible. Detecting their signals is therefore a critical scientific challenge.

This report addresses the problem by proposing a method for detecting random signals from hidden transmitters. The approach is based on differential signal transformations within correlation theory. It is proven that this method accurately determines the correlation function, showing that a hidden transmitter's signal comprises the sum of all discrete components of the differential spectrum. This enables the identification of its parameters, distinguishing it from other random signals in the tested radio range.

Simulations confirmed the method's effectiveness by providing numerical parameters and graphical results, validating its reliability in detecting hidden transmitters.

Keywords: detecting signals, random signals, spectrum, discrete components, model, mathematical expectations.

Introduction

A vast array of methods exists for intercepting and recording acoustic information. The choice of a specific acoustic surveillance technique depends on operational conditions, objectives, technical feasibility, and, most importantly, the financial resources of the surveillance organizers. Among the most prevalent methods is the interception of speech signals via radio-emitting devices. The diversity of radio microphones is so extensive that continuous advancements in detection methods are required. Consequently, techniques for identifying radio microphone emissions are constantly evolving.

Ensuring information security is a multifaceted process. Numerous technical devices are employed to intercept and record confidential data, with the majority transmitting acquired speech information over radio channels. Therefore, the primary challenge is detecting radio-based covert information acquisition systems. One promising approach is the detection of such signals using differential transformation methods.

The proposed method leverages differential transformations, a relatively novel operational technique. Unlike traditional integral and discrete transformations, this mathematical approach is based on converting original signals into the image domain through differentiation. Mathematical modeling of radio monitoring processes via differential transformations is distinctive in that it accounts for random disturbances affecting the monitoring process. The detection of an extraneous radio signal, such as that emitted by a radio microphone, is inherently stochastic. This characteristic necessitates advanced modeling techniques capable of accurately representing the conditions under which random signals are identified.

Simulating stochastic processes within complex nonlinear systems requires substantial computational resources. In real-time systems, the computational speed necessary to achieve the required accuracy for simulating stochastic processes may exceed the capabilities of contemporary computing technology. Therefore, the development of a mathematical method that enables real-time simulation of the detection process for random signals—based on a model for identifying hidden transmitters — remains a highly relevant scientific challenge.

Literature analysis and problem statement

The occupancy of the radio range for communication and data transmission is constantly increasing. Currently, almost the entire available radio frequency spectrum is used for the operation of various radio transmitters.

A wide range of radio scanning tools is used to detect means of covertly obtaining information [1]. In particular, monitoring systems capable of scanning and storing panoramas of signal spectra are popular and inexpensive [2, 3]. At the same time, such systems, as a rule, do not allow solving the task of analyzing legal digital communication channels due to the unsatisfactory quality of the radio receiving path.

Thus, in works [4,5] attention is drawn to many different methods of spectral analysis. It is shown that the methods of spectral analysis of random signals are divided into two large classes - non-parametric and parametric. In non-parametric methods, only the information contained in the data of the analyzed signal is used. Parametric methods assume the presence of a certain statistical model of a random signal, and the process of spectral analysis in this case contains the determination of the parameters of this model. But the issue of spectral analysis of random signals in order to determine the numerical values of the amplitudes of the spectrum of radio signals is not considered.

In works [6, 10-12], attention is paid to the complex Fourier transform. It was determined that complex transformation plays a significant role in signal analysis. The Fourier transform (FT) and its discrete analogs (DFT) are well known and widely used in spectral analysis methods in standard radio signal processing. This method is computationally efficient. It is easy to implement. As a rule, this method and procedures give good results when analyzing the frequency composition of long-duration radio signals. However, there are known reasons that limit the use of Fourier transforms in the analysis of pulse-short signals such as digital radio pulses, for example, using DFT for time-shortened signals leads to the Gibbs effect, which distorts information about the signal spectrum and does not allow obtaining high accuracy in the spectral region when analyzing harmonic components. Therefore, this method is not universal and has disadvantages that prevent the analysis of pulse signals.

A large number of works [7,13,14] pay attention to the use of modernized Fourier transforms. In most digital processing problems, it is not possible to test a signal at an infinite interval. It is impossible to know what the signal was before turning on the device and what it will be in the future. Also, the limitation of the research interval can be caused by the non-stationarity of the investigated signal. therefore, the modernized Fourier transform arose. In the modernized transformation, the limit of the analysis interval is equivalent to the product of the output signal by the window function. Thus, the result of the window Fourier transform is not the spectrum of the original signal, but the spectrum of the product of the signal by the window function. The spectrum obtained using the windowed Fourier transform is an estimate of the spectrum of the original signal and, in principle, allows for distortion. The distortions introduced by the use of windows are determined by the size of the window and its shape. There are two main properties of the frequency characteristics of windows: the width of the main lobe and the maximum level of the side lobes. The use of windows other than rectangular windows is due to the desire to reduce the impact of side petals by increasing the width of the main one. This improves the estimation of the spectra but does not solve the problem completely. But when using a windowed Fourier transform, it is impossible to provide a good time and frequency resolution at the same time. The larger the window, the higher the time resolution and the lower the frequency resolution. Therefore, the modernized Fourier method is also not fully satisfactory for the spectral analysis of pulsed radio signals.Spectrum analyzers and measuring receivers of the Rohde & Schwarz type [15] are more promising. They can solve the problem of finding means of surreptitious recording of information exclusively from the analysis of the radio spectrum. But they are not capable of analyzing digital signals and performing the task of locating the means of surreptitiously capturing information.

Vector analyzers are used for research and demodulation of signals of high-speed radio interfaces and signals with spectrum expansion [16]. However, these devices are designed to work together with receivers and spectrum analyzers, i.e. they cannot perform search and localization tasks on their own.

So, from the conducted analysis, it can be concluded that today there are no devices (devices, software packages) for the analysis of digital packets in order to solve the task of searching radio control. The task of finding a modern embedded device in the conditions of a complex radio environment remains unsolved. Therefore, the task of developing new methods for detecting signals of hidden radio microphones is relevant at the present time.

The main section

Differential transformations are a relatively new operational method, which, in contrast to the known, integral, and discrete transformations, are based on the translation of the originals into the mapping area using the differentiation operation. The main characteristics of random signals will be considered in the framework of correlation theory. Consider a one-dimensional random signal that was - a given random variable. In the mapping area, the model of this signal is represented by the differential spectrum.

To do this, we present a random signal as a random process implementation $X(t,\Omega)$, which is an integral representation of the solution of a stochastic nonlinear differential equation of the form:

$$\frac{dX(t,\omega)}{dt} = ae^{-\frac{1}{2}(\omega t - t_0)} \quad \omega \in \Omega\,,\ a = const, \tag{1}$$

with initial conditions $X(0,\omega) = 0$.

To determine the numerical parameters of a random process $X(t,\Omega)$, expectation $m_x(t)$ and variance $D_x(t)$ for the moment of time $t=\tau$ we make a differential transformation for the right-hand side of equation (1) by the following rule:

$$\underline{X}(k,\omega) = \frac{H^k}{k!}\left(\frac{d^k X(t,\omega)}{dt^k}\right)_{t=0}. \tag{2}$$

For equation (1), the image of the differential transform (2) has the form:

$$\underline{X}(0,\omega) = 0\,,\ \underline{X}(k,\omega) = \frac{H^k}{k!}(-1)^{k-1} 2^{1-k} \omega^{k-1} a e^{\frac{1}{2}t_0} \tag{3}$$

Table 3.1

Calculation data for five component values, for the expression (3)

k	$X(k,\omega)$
1	$Hae^{\frac{1}{2}t_0}$
2	$-\frac{1}{4}H^2\omega a e^{\frac{1}{2}t_0}$
3	$\frac{1}{24}H^3\omega^2 a e^{\frac{1}{2}t_0}$
4	$-\frac{1}{192}H^4\omega^3 a e^{\frac{1}{2}t_0}$

Having carried out the inverse transformation according to the formula:

$$X(t,\Omega) = \sum_{k=0}^{\infty}\left(\left(\frac{t}{H}\right)^k \underline{X_k}(k,\omega)\right) \tag{4}$$

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Expectation $m_x(t)$ of random process $X(t,\Omega)$ in the general the case is determined by the formula

$$m_X(t) = E\left(X(t,\Omega)\right) = \sum_{k=1}^{\infty}\left(\left(\frac{t}{H}\right)^k E\left(\underline{X}(t,\omega)\right)\right) \quad (5)$$

Using (2), (3) and (4). After the integration, we get:

$$\underline{m}_X(k) = \frac{H^k}{k!}(-1)^{k-1}\frac{1}{2\alpha}2^{1-k}ae^{\frac{1}{2}t_0}\int_{-\alpha}^{\alpha}\omega^{k-1}d\omega$$

$$\underline{m}_X(k) = \frac{H^k}{k!}(-1)^{k-1}\frac{1}{2\alpha}2^{1-k}\frac{\alpha^k-(-\alpha)^k}{k}ae^{\frac{1}{2}t_0} \quad (6)$$

Table 3.2

Calculation data for five component values for expression (6)

k	$\underline{m}_X(k)$
1	$Hae^{\frac{1}{2}t_0}$
2	0
3	$\frac{1}{18}H^3\alpha^2ae^{\frac{1}{2}t_0}$
4	0
5	$\frac{1}{600}H^5\alpha^4ae^{\frac{1}{2}t_0}$

Since at even values k the terms on the right-hand side of equality (6) are equal to 0, then, putting k=2m-1, in its final form, the representation (6) has the form:

$$\underline{m}_X(2m-1) = H^{2m-1}\frac{\alpha^{2m-2}}{(2m-1)!(2m-1)}2^{2-2m}ae^{\frac{1}{2}t_0}$$

$$m_X(t) = \sum_{k=1}^{\infty}\left(\left(\frac{t}{H}\right)^{2m-1}H^{2m-1}\frac{\alpha^{2m-2}}{(2m-1)!(2m-1)}2^{2-2m}ae^{\frac{1}{2}t_0}\right)$$

$$m_X(t) = \sum_{k=1}^{\infty}t^{2m-1}\frac{\alpha^{2m-2}}{(2m-1)!(2m-1)}2^{2-2m}ae^{\frac{1}{2}t_0}$$

Putting m= 1, m = 2, m= 3, finally we obtain the function of expectation of a given random process from time to time

$$m_X(t) = \left(t + \frac{\alpha^2}{72}t^3 + \frac{\alpha^4}{9600}t^5\right)ae^{\frac{1}{2}t_0} \quad (7)$$

By analogy, calculate the variance and represent the signal itself.

$$D_X(t) = E\left(\left(X(t,\omega)\right)^2\right) - \left(m_X(t)\right)^2;$$

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By introducing an additional variable

$$D_X(t) = E(V(t,\omega)) - (m_X(t))^2$$

Using the differential transformation, the dispersion image has the form

$$D_X(t) = \sum_{k=1}^{\infty}\left(\left(\frac{t}{H}\right)^k \underline{D}(k)\right) = \left(\frac{1}{72}\alpha^2 t^4 + t^4\right)a^2 e^{t_0}$$

Finally, the analytical dependence of the random signal as a function of time will look like this

$$X(t,\omega) = \begin{pmatrix} \frac{1}{1920}\omega^4 t^5 - \frac{1}{192}\omega^3 t^4 + \\ + \frac{1}{24}\omega^2 t^3 - \frac{1}{4}\omega t^2 + t \end{pmatrix} a e^{\frac{1}{2}t_0} \quad (8)$$

Simulation results

To confirm the developed method, the mathematical modeling of the radio signal detection process was performed. Using the developed model, the obtained graphic materials are shown in Figures 1 and 2.

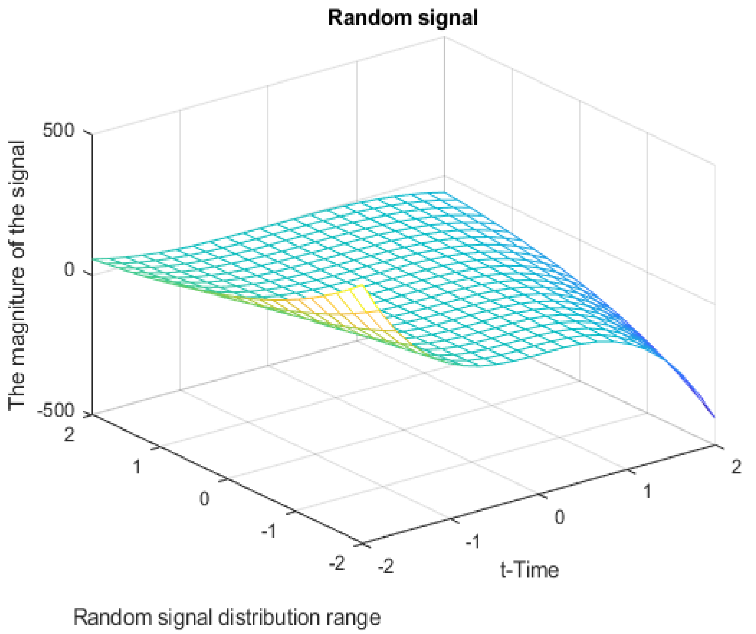

Figure 1. Random signal describing a digital signal of hidden transmitter

From the presented simulation results, we can see that the mathematical expectation, determined by calculation, completely repeats the given signal near the zero value, which is proof of the correct modeling of the process.

However, it should be noted that with an increase in the time or range of signal detection, the discrepancy increases, so the given technique just guarantees the calculation of a random signal with high quality, due to the fact that these signals are very short-lived.

Considering that the random signal is a stealth signal and is likely to run for a very short time, we did get good results for the impulse signal, but this signal is perfect. In practice, such signals do

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not exist, so I consider it expedient to necessarily determine not only the rate of decrease of the detected signal, but also to determine the rate of speed (acceleration) of the random signal.

The obtained results fully confirm the possibility of detecting radio signals based on the principle of determining the mathematical expectation and dispersion not of the signals themselves, but of the signals after their differential transformation.

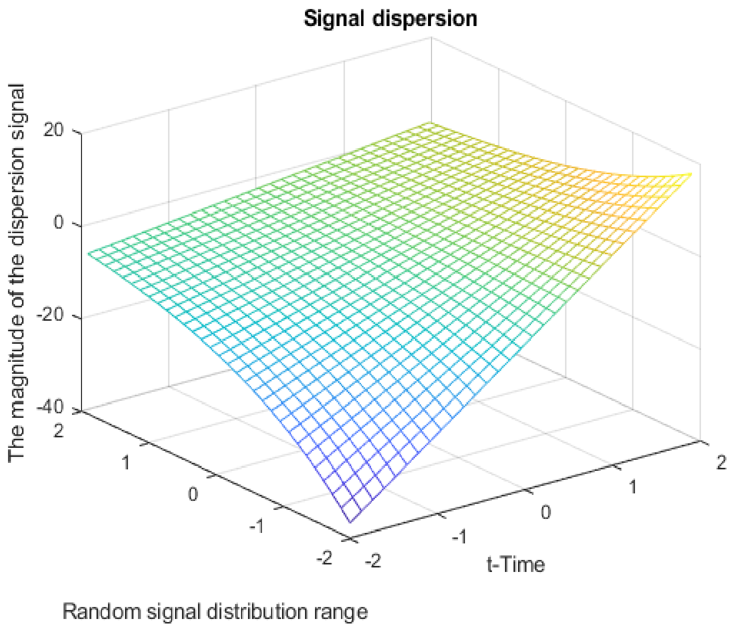

Figure 2. Expectation of a signal of a digital signal of hidden transmitte

Conclusions

The proposed mathematical approach is founded on the model of differential transformations applied to random signals. A mathematical model has been developed to precisely represent the signal and facilitate the determination of radio signal parameters. The methodologies for calculating these parameters enable the extraction of key statistical characteristics. It has been demonstrated that the correlation function is derived from two differential spectra and comprises the summation of all discrete components of the differential spectrum.

The results obtained through simulation have graphically validated the accuracy of the analytical findings. The proposed method enables the analysis of statistical characteristics for the detection and identification of random signals against the backdrop of legitimate radio transmissions. The findings confirm the adequacy of the mathematical model and its capability to detect concealed transmitters based on the theoretical framework of differential transformations.

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