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ANALYSIS OF COLOR NOISE EFFECT ON QUALITY OF RECOVERING THE CHAOTIC SIGNALS

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Recently, during the development of the modern information transmission systems, more and more attention has been paid to the search for new ways of forming and processing signals, which can simultaneously ensure the necessary level of stealth and speed of information transmission. Chaotic signals with OFDM modulation satisfy these requirements. However, the effectiveness of their functioning has investigated only during impact of the "white" noise. Nonetheless, in real radio communication channels there are other types of noise, which called color noise. Such noises occur due to interference in the environment of propagation of radio signals and in the signal generation tools.

In article has been analyzed the influence on chaotic signals with OFDM-modulation noises of different colors. The noises have generated by lineal integral transformation of “white” noise with Mandelbrot’s kernel. The obtained results showed that if in received signal presence the useful signal and one type of color noise (“white”, “pink”, “black”) the required level of message recovery is achieved with approximately equal signal/noise ratios. The number of subcarriers in chaotic signal with OFDM-modulation influence on the quality of recovering, their increase leads to the increase the required signal to noise ratios on the receiver side.

However, during the presence in received signal additive mixture of useful signal, “white” and “color” noise the necessary level of recovery the binary message can be obtained during the signal to “white” noise ratio more than 18 dB, and signal to “color” noise ratio should be not less than 16 dB. The obtained results have showed the necessary of development methods to increase the quality of recovery chaotic signals with OFDM-modulation under the influence of colored noises.

Keywords: *the information transmission system, color noises, OFDM, signal-to-noise ratio, probability of correct estimation.*

I. INTRODUCTION

Today, the electronic means that ensure the control of troops and forces provide a potential opportunity for the enemy to reveal our combat capabilities, actions and intentions, as well as to prevent our use of these means by destroying them or by radio suppression. Taking into account the high-speed development of enemy electronic warfare means, there is a need to develop and introduce new types of signals capable of providing the necessary level of electronic protection of our communications. [1-2]. This can be achieved by ensuring a high level of secrecy of the signals used in information transmission systems, since in this case the enemy will not be able to detect, determine the type and reveal the information transmitted by the radio signal [3-6]. One of the possible ways to form signals with a high level of secrecy is to use chaotic processes and sequences whose properties are close to the properties of "white" noise. As signs of chaotic signals, the topology of the set of signal points in pseudophase space is used. [7]. As a numerical measure of the proximity of chaotic signals to "white" noise (Independent and Identically Distributed (IID)-stealth) use non-parametric Brock Dechert Scheinkman (BDS)-statistics [3-7].

However, when using chaotic signals in real communication channels, the question arises as to the effectiveness of their recovery on the receiving side, especially given that they are influenced not only by "white", but also by color noise. The paper considers the problem of assessing the quality of recovery of chaotic signals with OFDM-modulation with analytical chaotic signals during exposure to color noise.

II. ANALYTICAL REVIEW OF THE LITERATURE

2.1. General information about signals with OFDM-modulation

Currently, active work is underway around the world to introduce and expand the areas of application of wireless data transmission, radio communications, radio broadcasting and television, based on signals with OFDM-modulation. Developed in the 60s of the last century, signals with OFDM-modulation due to the imperfection of the then technologies became available for use only relatively recently [8]. It was first used about 40 years ago in several military systems: KINEPLEX, ANDEFT and KATHRYN. Thus, the KINEPLEX TE-206 data transmission system provided transmission at a speed of 2400 bit/s using 8 channels (sub-carriers), and TE-202 – 3000 bit/s using 40 channels. In this case, the frequency spread between the subterfuges was not less than or equal to $\Omega = 2\pi / T$ (T – length of the clock interval), because with mutually incoherent sub-carriers it is impossible to ensure their orthogonality with less peddling [9].

As areas of application of signals with OFDM-modulation can be identified [9]:

– in the standards of digital terrestrial broadcasting: DVB-T, DVB-T2, DVB-H, DVB-SH, DVB-T2lite, T-DMB, ISDB-T, MediaFLO, Eureca-147, DAB, DAB+, DRM, DRM+;

– in wired communication channels used in the standard of cable digital television broadcasting DVB-C2 and data transmission ADSL, VDSL;

– for data transmission over a power line based on the PLC standard;

– in data transmission standards IEEE 802.11a/g/n/ac, IEEE 802.16d/e, IEEE 802.16m, LTE, LTE-A and future 5G generation networks;

– in ultra-wideband data networks based on the IEEE 802.15.3a standard (Ultra-Wideband Technology, UWB) and its subsequent developments;

– in satellite and radio relay communication systems;

Signals with OFDM-modulation were widely used in military radio communication systems of the power structures of the world. NATO ground forces have developed communication systems using the military version of the IEEE 802.11g standard. by MobiComm. Nova Engineering offers serial communication systems for the US Navy (HDRLOS Radio Modem), which implement the principle of OFDM. The wide distribution of OFDM was facilitated by the choice of this signal modulation technology as the physical basis for the creation of tactical broadband networks (Wideband Networking Waveform WNW) within the framework of the Joint Tactical Radio System (JTRS) program. In the long-term plan for the development of unmanned aircraft systems of the United States, it was noted [10] that WNW is planned to be used as radio communication lines with an unmanned aerial vehicle (UAV) based on WiBro technology (Wireless Broadband, IEEE 802.16).

The principle of operation of signals with OFDM-modulation is that the available frequency band is divided between the set of subcarrier frequencies. In addition, each subsurface can be modulated using different types of digital modulation (BPSK, QPSK, QAM). Thus, in the time domain, a complex signal with OFDM modulation can be written as follows. [8]:

$$S_k = S(k\Delta t) = \frac{1}{N}\sum_{n=0}^{N-1}\dot{U}_n e^{jnk\frac{2\pi}{N}} \qquad (1.1)$$

where N is the number of subcarriers; $k = 0,1,2,3...(N\text{-}1)$ – Discrete time; Δt – Sampling period; $\dot{U}_n$ – complex information symbol [5-8].

As a result of the use of signals with OFDM-modulation, all characters are transmitted simultaneously while the duration of each character effectively increases N times compared to the sequential transmission of characters at the same frequency.

In case of frequency separation of subcarrier*s*, it is necessary that on the one hand the width of each is narrow enough to minimize the curvature of the signal within its limits, and on the other wide enough to ensure the required speed of information transmission. In addition, for the economical use of the entire bandwidth of the channel, divided into subcarriers, it is necessary to place them as close as possible near each other, while avoiding interchannel interference to ensure complete independence of the subcarriers from each other. In signals with OFDM-modulation, this is realized using orthogonal frequency sub-carriers, that is, the condition is met:

$$\int_0^T \sin 2\pi f_l(t)\sin 2\pi f_k(t)dt = 0, k \neq l \qquad (1.2)$$

where T is the duration of the symbol; f_l and f_k – the frequencies of the l-th and k-th subcarriers, respectively.

Orthogonality between subcarriers is ensured only when, during the duration of one symbol T, the carrier signal will perform an integer number of oscillations. Since each symbol of duration T is transmitted by a time-limited sinusoidal function, its spectrum is described by a function of the type:

$$\frac{\sin 2\pi(f - f_i)}{2\pi(f - f_i)} \tag{1.3}$$

where f_i is the central (carrier) frequency of the i-th channel. The same function describes the shape of the subchannel.

The spectra of the subcarriers overlap with each other without interference, as shown in Figure 1. 4. Orthogonality allows on the receiving side to select each subcarrier from the total number, despite the partial overlap of their spectra. Due to this, a high spectral efficiency of the modulated OFDM signal is achieved. [9-11].

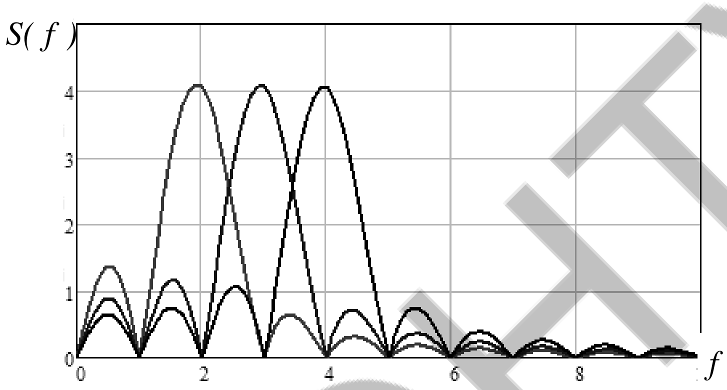


Fig. 1.1 – Spectrum of the subcarriers signal with OFDM-modulation

The implementation of a system with signals with OFDM-modulation, which consists of generators in the transmitter and a set of matching filters in the receiver, is quite difficult for a large number of subcarriers. Therefore, for the rapid implementation of signals with OFDM-modulation using computing devices, the algorithm of direct and inverse fast Fourier transform (FFT) is used. With the help of an inverse FFT in the transmitter, the sum of the subcarriers obtained as a result of modulation is "collapsed" into one, which is converted into a digital form and transmitted to the communication line. Further, on the receiving side, the conversion from a digital form to an analog one occurs, a direct FFT is performed, after which the subcarriers are demodulate into one sequence.

Signals with OFDM modulation are used by many wireless and wired communication standards due to the following advantages:

1. Resistance to narrowband interference. When using signals at one carrier frequency, fading or interference can lead to loss of information, at the same time a small amount of information will be damaged in signals with many subcarriers.
2. Resistance to frequency-selective fading, due to parallel transmission (each sub-carriers has a narrow frequency band relative to the total width of the signal band).
3. High spectral efficiency, which ensures the orthogonality of the subcarriers among themselves.
4. The use of multi-position types of modulation to increase the speed of data transmission.

However, the disadvantages of using signals with OFDM modulation include:

1. During the appearance of the Doppler effect in a signal with OFDM modulation, a change in the central carrier frequency occurs, which leads to a change in the entire spectrum of the useful signal, which in turn leads to a violation of the orthogonality of the subcarrier frequencies.
2. High peak factor value (8 ... 12 dB).
3. The protective interval used in signals with OFDM modulation to combat multi-beam propagation reduces the spectral efficiency of the signal.
4. Low level of secrecy of such signals during their use in secure information transmission systems [12].

2.2. The principle of constructing chaotic signals with OFDM-modulation

In most modern radio engineering transmission systems, harmonic oscillations are used as an information carrier [11-14]. The information signal in the transmitter modulates these oscillations by amplitude, frequency or phase, and in the receiver information is released through the reverse operation – demodulation. Modulation of the carrier can be carried out, either by modulating already formed harmonic oscillations, or by controlling the parameters of the generator in the process of oscillation formation.[14].

However, the need to resist the means of unauthorized access to information puts forward increased requirements for solving the problem of ensuring its protection, which information transmission systems with harmonic signals cannot provide. Therefore, in [3-6] it is proposed to use dynamic (deterministic) chaos. The main feature that distinguishes it from ordinary noise is that it is implemented using a specific mathematical algorithm, which allows you to reproduce it on the receiving side. Modulation of chaotic signals by information can be carried out in the same way as for harmonic ones. However, the possibilities here are much wider. Indeed, if in the case of harmonic signals of controlled characteristics – only three (amplitude, phase and frequency), then in the case of chaotic oscillations, even a small change in the control parameter gives a reliably fixed change in the nature of the oscillations [15]. Chaos generators with changing parameters have a wide range of schemes for entering an information signal into a chaotic one (that is, modulating a chaotic signal with an informational one). In addition, interest in chaotic signals is related to the fact that that they are broadband, that is, they have a greater information capacity. In communication systems, a wide frequency band of carrier signals is used both to increase the transmission rate and to increase the stability of the systems in conditions of interference [15]. This property of chaotic processes is most often used to encode information [4-7].

Recently, broadband methods of chaotic modulation have been in the spotlight. They consist in modulating information bits by chaotic implementations, which are obtained through appropriate chaotic reflections. Chaotic implementations have broadband and non-periodicity properties and a pulsed autocorrelation function. Typically, systems with chaotic modulation are divided into coherent, for which it is necessary to have a copy of the original chaotic implementation in the receiver, and incoherent, in which the signal detection process does not require such a copy. To evaluate discrete reflections from the point of view of ensuring secrecy when using them as models of chaotic oscillation generators, we will further use the following indicators: autocorrelation function, energy spectrum and degree of homogeneity of "image" points in pseudophase space. It is important that the values of the control parameters of the imaging are those that would provide an autocorrelation function with a narrow peak and low lateral emissions, a uniform and broadband energy spectrum in the frequency band, and the proximity of the "image" in pseudophase space to the "image" of "white" noise [16].

Taking into account the possibilities of chaotic reflections to provide the necessary level of secrecy of information transmission systems in the work [17], a method of forming sub-carriers for chaotic signals with OFDM-modulation using one-dimensional chaotic reflection of Chebyshev's polynomials of the 1st kind of the 3rd order was proposed and investigated (Fig. 1. 2):

$$x_{n+1} = 4x_n^3 - 3x_n, \tag{1.4}$$

where $n = 1 \ldots N$ – the number of samples in the sequence; x_0 – the initial value of the sequence.

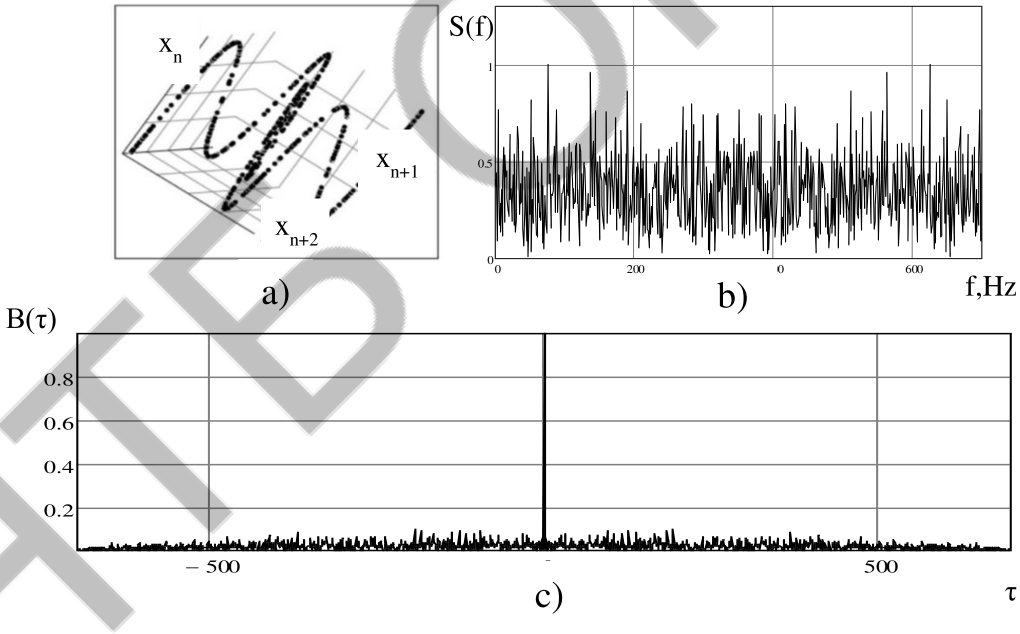


Fig. 1. 2 – Reflection of the Chebyshev polynomial 1 of the kind 3 order: a) "image" in pseudophase space; b) the energy spectrum; c) autocorrelation function

It is known [4-7] that the disadvantage of using such reflections is the structure of their "images" in pseudophase space, which significantly distinguishes them from random processes. Therefore, to complicate the structure of the "image" and change the statistical characteristics of the input chaotic sequence, the authors [17] used the concept of an analytical signal [3]. On a set of discrete values, an analytical signal was obtained in a complex form, according to the expression $\dot{x}_n = x_n + jy_n$, where $y_n = \{y_0, y_1, \dots y_{N-1}\}$: the imaginary part of the analytical signal is given by the Hilbert transformation to the input sequence $x_n = \{x_0, x_1, \dots x_{N-1}\}$. The application of the Hilbert transform provides amplitude $A_n = \sqrt{x_n^2 + y_n^2}$ and phase $\psi_n = \arctan\left(\frac{x_n}{y_n}\right)$ signal [3]. After transferring the complex amplitude to the harmonic frequency of modulation, an analytical chaotic sequence (ACS) was obtained in the form of $s_n = \mathrm{Re}(A_n e^{j\omega n}) = A_n \cos(\psi_n + \omega n)$. Further, to organize the secretive transfer of information, elements of the "1" information sequence $\{r_v\}_{v=1}^{V}$ (r is 0,1 were transmitted with frequency in ACS ω_1, and elements "0" with ω_2, according to:

$$s_n = \begin{cases} A_n \cos\left(\psi_n + \omega_1 n\right), & r = 1, \\ A_n \cos\left(\psi_n + \omega_2 n\right), & r = 0. \end{cases} \tag{1.5}$$

During the transition from a discrete chaotic signal to its continuous representation in a given frequency band in the range from 0 to some upper limit frequency $f_{\text{в}} = F$ the method of interpolation of Shannon – Kotelnikov was used [5]. It has been suggested that the expression (1.5) is a narrowband process that is fully determined by the sequence of its instantaneous values $\{s_n = s(nT_0), n = 0, \pm 1, \dots, \pm N-1\}$, the distance between which is equal to the interval $T_0 \le 1/2F$. Then, after transferring the received signal to the carrier frequency, the chaotic signal with OFDM-modulation (OFDM-ACS) can be recorded:

$$s(t) = \sum_a \left(\sum_n s_{a,n} \gamma_n \cos\left(2\pi f_a \left(T_0 t - n\right)\right) \right), \tag{1.6}$$

where $\gamma_n(t) = \mathrm{sinc}\left(T_0 t - n\right)$; $f_a = aF$, $f_1 = 2F, a = 1\dots A$ – numbers of transmitted chaotic sub-carriers.

However, the authors [17] investigated the quality of message recovery formed using chaotic signals with OFDM-modulation (1. 6) only when exposed to "white" noise. However, when receiving signals against the background of noise, the use of the "white" Gaussian process model is not always advisable, since in it all frequencies affect the signal equally [18]. While, for example, the use of "brown" (Brownian) noise has a greater effect on low frequencies, and "black" on high frequencies. Therefore, for a more complete analysis of the effectiveness of the functioning of ITS with chaotic OFDM-ACS signals, it is necessary to investigate the effect of fractal (color) Gaussian noise on them. In [19] the authors made an assessment of the effect of color noise on radio communication channels. The statistical and spectral properties of noise were analyzed and it was shown that color noises are always present in the received radio signals along with the "white" noise. To assess the presence of color noise components in the adopted implementation, the Leung-Box statistical test was used, which tests the null hypothesis that the accepted time series is "white" noise. Calculations of the probability of correct message recovery for wireless communication channels showed that the presence of an additive mixture of color and "white" noise significantly reduces the reception quality. This indicates the need to take into account such noise when modeling real communication channels.

The paper [20] describes the dispersion estimation algorithm, which refutes that the resulting process is "white" noise. As real signals, sub-carriers of signals with OFDM-modulation were chosen. The obtained algorithm takes into account the real radio signal propagation medium, where noise is not characterized by constant spectral power. This situation often occurs when exposed to severe interference. The intensity of color noise in the signal is detected by calculating the autocorrelation of the spectral power density. At the same time, when noise is not colored, the proposed algorithm works in the same way as traditional calculators of the dispersion of "white" noise.

Below we will consider the problem of assessing the probability of correct recovery of a message from chaotic OFDM-ACS signals against the background of "white" and color noise.

III. OBJECT, SUBJECT AND METHODS OF RESEARCH

The object of study - random, chaotic and regular processes in radio engineering systems of information transmission.

The subject of the study - the study of the influence on chaotic signals with OFDM-modulation of color noise by methods of the statistical theory of information-measuring systems.

Research methods. During the solution of the tasks, modern methods of digital signal processing, classical and non-traditional mathematical statistics, methods of nonlinear dynamics, methods of the statistical theory of observation processing, simulation and statistical modeling in the Mathcad application package were used.

IV. WORK RESULTS

Let us investigate the effect of colored noise on the signals formed according to (1.6). To model colored noises, we will use the linear integral transformation of "white" noise with the Mandelbrot kernel and its discrete approximations, which generalize Brownian motion and allow us to obtain a set of random processes with different fractal dimensions [7]:

$$\Delta B_H(t) \approx \frac{n^{-\frac{1}{2}}}{\Gamma\left(H+\frac{1}{2}\right)}\left[\left[\sum_{i=0}^{[n\cdot(t+1)]-1}\left((t+1)-\frac{i}{n}\right)^{H-\frac{1}{2}}\eta_i\right]-\left[\sum_{i=0}^{tn-1}\left(t-\frac{i}{n}\right)^{H-\frac{1}{2}}\eta_i\right]\right]$$

(1.7)

or

$$\Delta B_H(t) \approx \frac{n^{-\frac{1}{2}}}{\Gamma\left(H+\frac{1}{2}\right)}\left[\begin{array}{l}\left[\sum_{i=nt}^{[n\cdot(t+1+M)]-1}\left((t+1+M)-\frac{i}{n}\right)^{H-\frac{1}{2}}\eta_i\right]- \\ -\left[\sum_{i=nt}^{n(t+M)-1}\left(t+M-\frac{i}{n}\right)^{H-\frac{1}{2}}\eta_i\right]\end{array}\right] \qquad (1.8)$$

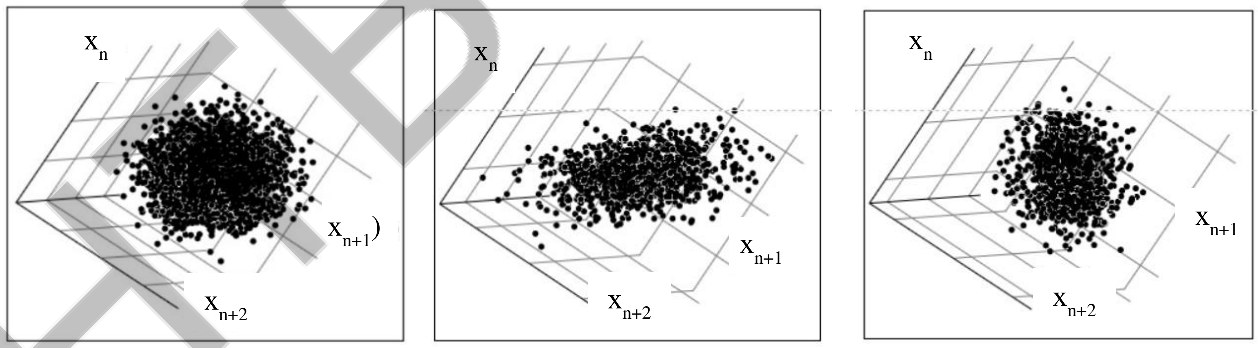
where $\{\eta_i\}$ – "white" noise with zero mean and unit variance with $i = 1, 2, \ldots, M, \ldots$;

n – a kernel parameter that sets the final capacity;

M – filter order;

H – the Hurst index (coefficient of self-similarity), which takes values from the interval [0, 1].

Expressions (1.7) and (1.8) are equivalent to calculating the average value from "white" noise for positive values of time with a power-law weight function that has no features for the values. Expression (4) allows using a fixed number of elements of the generation process, which is equivalent to calculating a moving average in a window with *nM* integer steps. Depending on the value of the Hurst indicator in (1. 8) it is possible to get different types of color noise. "Images" of processes in pseudophase space at different values of the Hurst indicator are shown in Fig. 1. 3.



a) b) c)

Fig. 1.3 "Shapes" of processes in the pseudo-phase space at the values of Hurst exponent: a) – $H = 0.5$ (“white” noise); b) – $0.5 < H < 0.9$ (“black” noise); c) – $0 < H < 0.5$ (“pink” noise).

From Fig. 1.3 shows that at $0 < H < 0.5$, the points on the "image" in the pseudophase space are grouped along the diagonal with a negative derivative. This indicates a decrease in dependence in the data and antipersistence is observed ("pink" noise), that is, if the values of the process increase in the previous period of time, it is most likely that they will fall in the next period, and vice versa. Independent and equally distributed values formed in the Mandelbrot kernel, when $H = 0.5$. On the interval $0.5 < H < 0.9$ (fig. 1c) a rotation of the "shape" in the pseudo-phase space of the transformed process has observed in the direction of the diagonal with a positive derivative. It indicates an increase in the dependence between the values of the modeling process and its desire for persistence ("black" noise). The property of persistence indicates the desire to preserve the trend in the evolution of the process. A persistent process has a long-term memory, which manifested in an increase in the horizon of predictability of the process and strong correlations between its values, which lag far behind each other. Table 1.1 shows the types of color noise depending on the value of the Hurst coefficient *H* in (1.8).

Table. 1.1 – The property of persistence indicates the desire to preserve the trend in the evolution of the process. A persistent process has a long-term memory, which manifested in an increase in the horizon of predictability of the process and strong correlations between its values, which lag far behind each other. Table 1.1 shows the types of color noise depending on the value of the Hurst coefficient *H* in

Color of noise	**The value of the Hurst coefficient, *H***
"brown"	H~0.1
"pink"	H~0.3
"white"	$0.4 \leq H \geq 0.6$
"grey"	$0.6 < H \geq 0.7$
"black"	$H > 0.7$

It has to be noted that on receiver enters an additive mixture of the useful signal and noise. Therefore, processing of such signal must carry out using known methods of the statistical theory of radio engineering systems. For this purpose, after receiving the signal and dividing it into subcarriers, it is possible to perform correlation processing of the received signal [21]. To determine the frequency in ACS, at which "0" or "1" transmitted, the input signal in the duration interval of one symbol multiplied by a set of ACS with different frequencies $\{\omega_i = i\Delta_\omega\}_{i=1}^{100}$, that change with the step $\Delta_\omega = 0.01$. Afterward, the frequency in the ACS determined based on the maximum response and accepted one of the two hypotheses: H_0 – a message element with an ACS frequency ω_0, or H_1 – a message element with an ACS frequency ω_1.

It is important to investigate the probability of correct message recovery depending on the SNR *q* at the receiver input. The probability of correct message recovery and SNR determinate according to [21]:

$$P_{rec}(q) = k(q) / K, \tag{1.9}$$

where *k* – the number of realizations in which the condition of correct recovery effect for SNR *q*;

K – total number of tests.

and

$$q = 10\lg\left(\sigma_s^2 \big/ \sigma_n^2 \right), \tag{1.10}$$

where σ_s – power spectral density of the useful signal;

σ_n – power spectral density of the noise.

Figure 1.4 shown the simulation data of the binary message elements discrimination using correlation processing of the input signal against the background of colored noise with different values of the Hurst index in (3.2) (*H=0.3, H=0.5, H=0.9*). The total number of tests equal *K = 1000*.

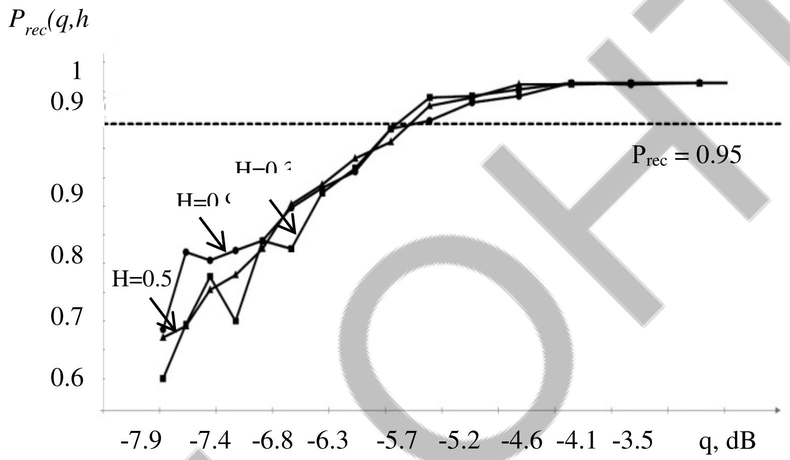
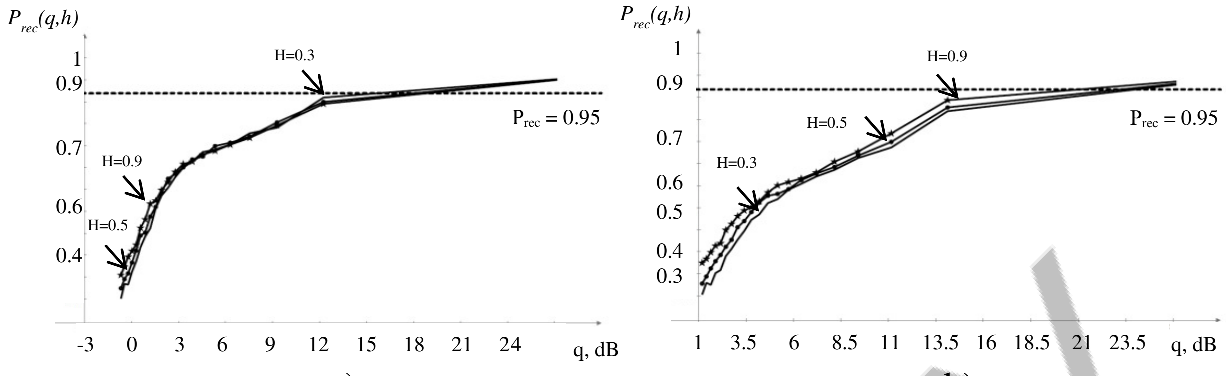


Fig. 1.4 – The probability of correct message recovery depending on the value of the Hurst's index in the chaotic signal with OFDM-modulation.

The analysis of the obtained results shows that the color of the noise has a slight effect on the probability of correct message recovery of a chaotic signal with OFDM-modulation. At the value of the SNR *q=-5dB*, the largest P_{rec} obtained against the background of "pink" noise, while for "white" and "black" noises it 0.01 lower.

However, it necessary to give an empirical estimate of the probability of correct message recovery $P_{rec}(q,h)$ depending on the number of subcarriers *h* in the signal with OFDM- modulation (3.9) and the SNR. By noise mean the presence of "white" noise (*H=0.5*), "pink" (*H=0.3*) and "black" noise (*H=0.9*). Figure 1.5 shows the $P_{rec}(q,h)$ values for 4 and 8 subcarriers in signal with OFDM-modulation depending on the SNR of color noise. The total number of tests equal *K=1000*.



a) b)

Fig. 1.5 The probability of correct message recovery depending on the noise color and the number of subcarriers in chaotic signal with OFDM-modulation: a) h=4; b) h=8.

The analysis of the figure 1.5 indicates that with an increase in the number of subcarriers *h* in signal with OFDM-modulation, the required level of probability of correct message recovery $P_{rec} \geq 0.95$ provided at higher SNR. At *h=4*, the SNR should be *q≥18 dB*, and at *h=8*, *q≥23 dB*. It means that an increase the number of subcarriers increases *q* by *5 dB*. Also, it can be concluded that the color of the noise does not make significant additional changes in the probability of correct message recovery. However, it should be noted that at the input of receiver observed an additive mixture of the useful signal and noise, which can be represented by the sum of "white" and colored noises. Therefore, Figure 1.6 shows the curves of probability of correct message recovery of chaotic signal with OFDM-modulation on *h=8* subcarriers when in the input signal presence the sum of "white" and "pink" noises and of "white" and "black" noises. The total number of tests equal *K=1000*. The power spectral density of color noise equal to σ_n=1.

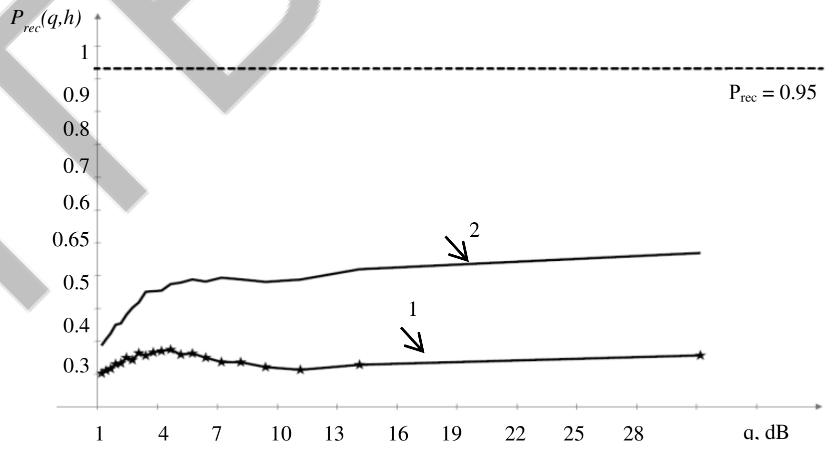
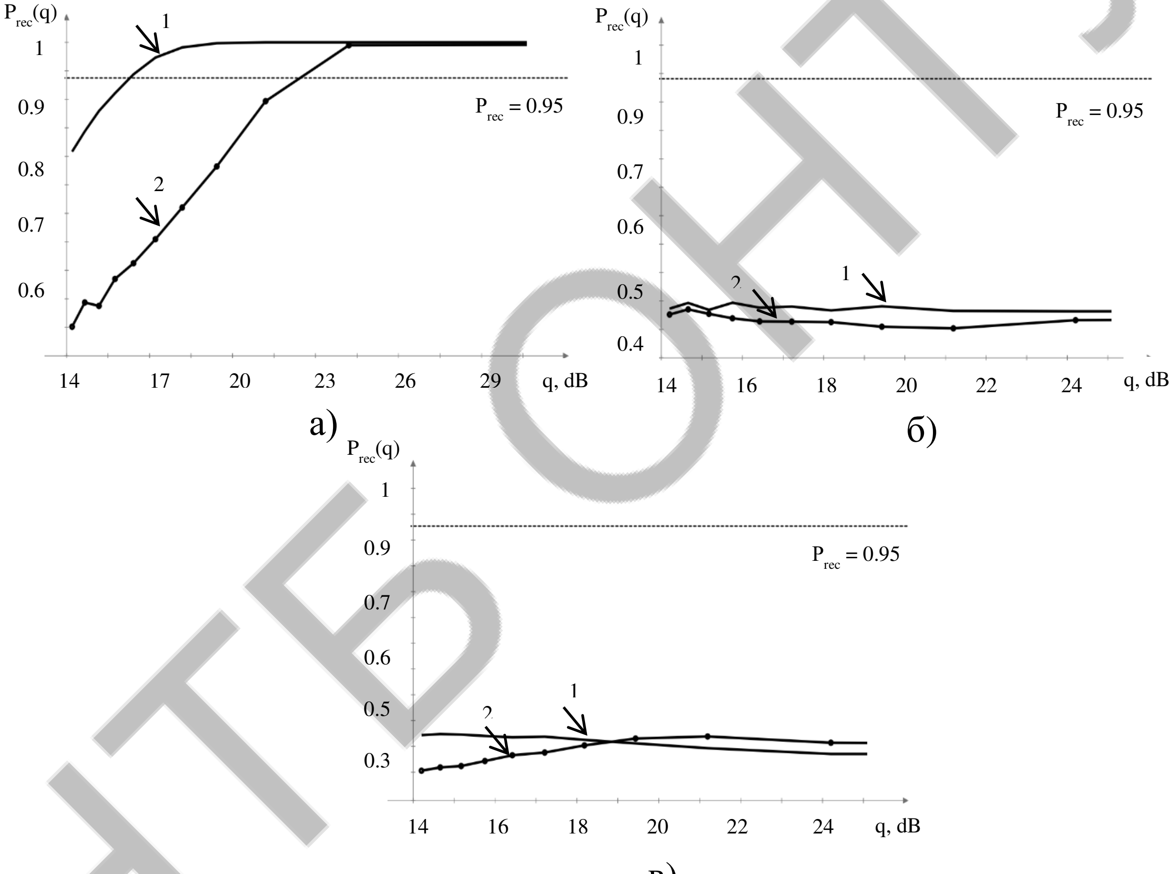


Fig. 1.6 – The probability of correct message recovery of a chaotic signal with OFDM-modulation on h=8 subcarriers when in the input signal presence the sum of "white" and "pink" noises (1) and of "white" and "black" noises (2).

The analysis of the obtained dependencies (Fig. 4) indicates that the presence of an additive mixture of the useful signal, "white" and color noise in the receiver input leads to a significant deterioration of the reception quality, in which the required level of $P_{rec} \geq 0.95$ not provided at all. Moreover, the additive mixture of "white" and "pink" noise has the greatest negative impact on chaotic signals with OFDM-ACS-modulation. For a more detailed study of the outflow of color noise to chaotic OFDM-ACS signals, it is necessary to investigate the probability of correct recovery of the message from such signals during a change in the power of the signal/color noise ratio and the constant value of "white" noise. For this Fig. 1.7 shows the probability curves of correct recovery of the message from chaotic OFDM-ACS signals to 8 subcarriers depending on the power of "black" and "pink" noise and the signal/noise ratio q = 18 dB, q = 11 dB, q = -1 dB.



а) б)

в)

Fig. 1.7 – The probability graph of the correct recovery of the message from the chaotic signal OFDM-ACS to 8 subcarriers, depending on the power of the "pink" noise (1) and "black" noise (2) at a constant value of the signal/"white" noise ratio: a) q = 18 dB; b) q = 11 dB; c) q = -1 dB

Analysis of the obtained curves (Fig. 1.7) indicates that in order to effectively recover a message from chaotic OFDM-ACS signals during exposure to color noise, the signal/"white" noise ratio at the input of the receiving device must be q ≥ 18dB. In this case, the required level of recovery of the message P_{rec} = 0.95 is provided during the power of the "black" noise of 22 dB, while for the "pink" it is 6 dB less and equal to 16 dB. This indicates that the most negative impact on the chaotic signal OFDM-ACS has the presence of "black" noise in the radio communication channel.

To explain the results obtained, we construct the spectral power density in the frequency region of various noises and the generated signal (Fig. 1. 8) and their autocorrelation functions (Fig. 1. 9).

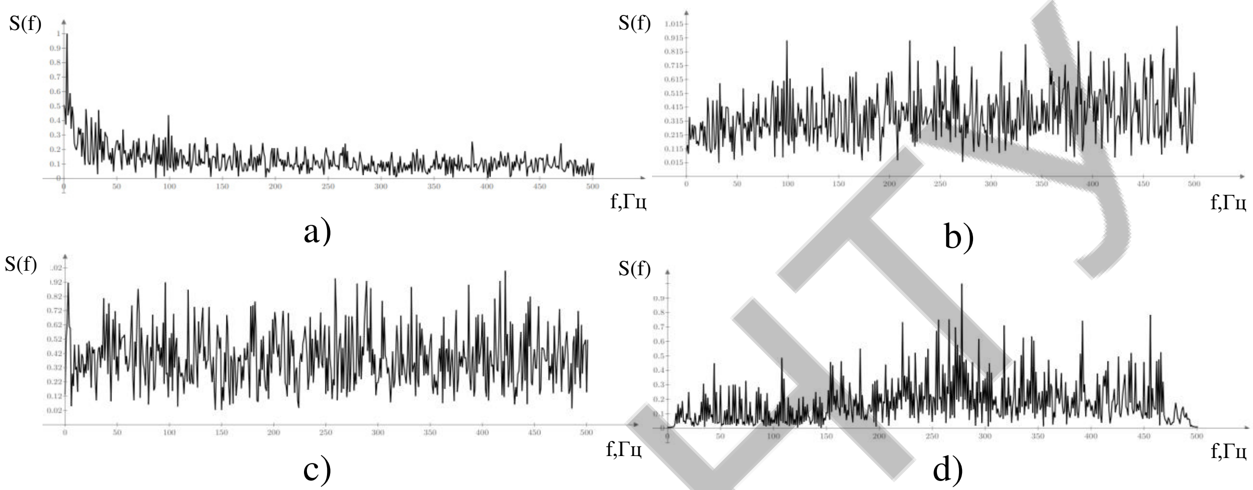


Fig. 1. 8 – Spectral power density in the frequency region of noise: a) "black"; b) "pink"; c) "white"; d) OFDM-ACS for 8 subcarriers

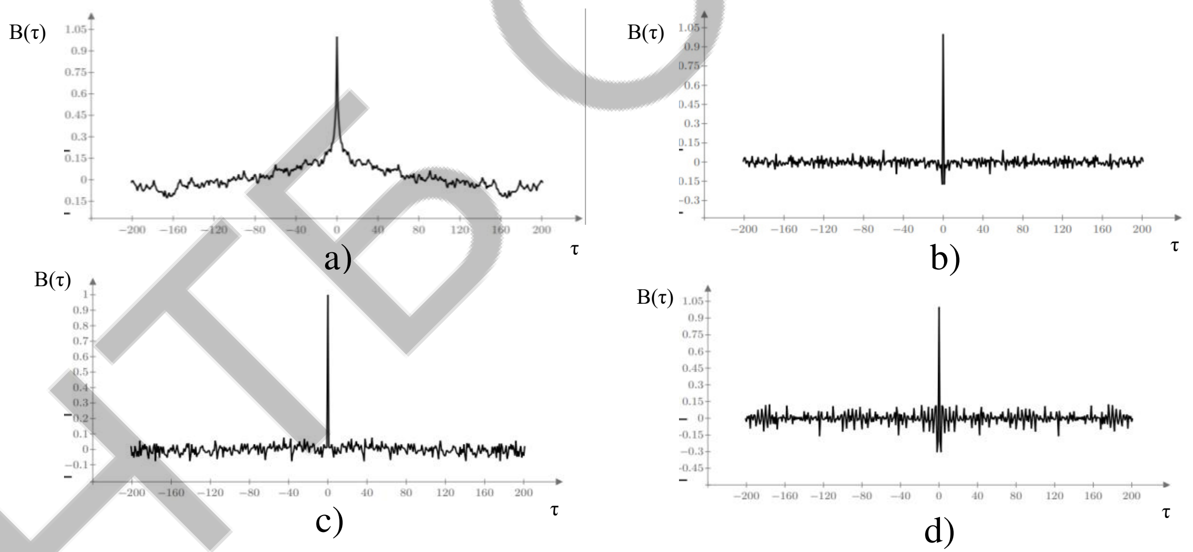


Fig. 1. 9 – Autocorrelation functions of noise: a) "black"; b) "pink"; c) "white"; d) OFDM-ACS for 8 subcarriers

The presence in the accepted implementation of only "white" noise (Fig. 1. 8c, 1. 9c) does not introduce significant distortions in the signal, since the spectral power density of such noise is constant at all frequencies, and the correlation intervals are close to zero. In this case, the correlation receiver is able to restore the message at lower signal-to-noise ratios. However, when adding a mixture of "white" and "pink" noise to the accepted implementation (Fig. 1. 8b, 1. 9b) the quality of recovery is reduced. This is explained by the fact that in the "pink" noise the correlation intervals between the values increase, and the spectral power density focuses on low frequencies. This all makes the process more correlated and increases the necessary signal-to-noise ratios to correctly restore the message in the correlator. However, the most negative effect on the quality of message recovery is the presence of a mixture of "white" and "black" noise (Fig. 1. 8a, 1. 9a), since in the "black" noise there are the largest correlation intervals, and the spectral power density is concentrated at high frequencies.

Thus, the proposed method of forming chaotic signals OFDM-ACS makes it possible to provide the necessary level of IID and structural secrecy of hidden information transmission systems. At the same time, in order to effectively restore such signals on the receiving side, the signal-to-noise ratio must be q ≥ 18 dB.

V.CONCLUSIONS

The work investigated the effect on chaotic signals with OFDM-modulation of noise of different colors. The noises were generated using a linear integral "white" noise conversion with the Mandelbrot core. The obtained results show that when there is a useful signal and one type of color noise ("white", "pink", "black") in the accepted implementation, the required level of message recovery is achieved approximately at equal signal/noise ratios. The quality of recovery is affected by the number of subcarriers in a chaotic signal with OFDM-modulation, their increase leads to an increase in the required signal/noise ratios at the receiver input.

However, during the presence in the adopted implementation of an additive mixture of the useful signal, "white" and color noise, the necessary level of restoration of the binary message $\mathrm{P}_{rec} \geq 0.95$ can be provided during the ratio signal/"white" noise at the input of the receiving device $q \geq 18dB$, and the level of the ratio signal/color noise should not be less than 16 dB. The obtained results indicate the need to develop methods for improving the quality of restoration of chaotic signals with OFDM modulation under the influence of colored noise.

VI.REFERENCES

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