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METHODS FOR EVALUATING THE IMPACT OF ENERGY AND CORRELATION PROPERTIES OF SIGNALS ON THE RESILIENCE TO INTER-CHANNEL INTERFERENCE IN INTELLIGENT RADIO SYSTEMS

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Key words: *Synthesized signals, inter-channel interference, correlation effects, energy characteristics, cognitive radio systems, signal generation methods, optimization methods.*
Abstract: *In the article, an in-depth analysis is carried out on methods for evaluating the impact of energy and correlation properties of signals on their resistance to inter-channel interference within intelligent radio systems. The study is pivotal in identifying new methodologies for signal generation, aiming to significantly enhance spectrum utilization and elevate the robustness of these systems against interference. By delving into the intricate dynamics of energy characteristics and correlation effects, the research proposes innovative mechanisms for the detection and compensation of interference automatically. This exploration not only emphasizes the critical need to consider energy aspects and the challenges posed by inter-channel interference but also sets the foundation for the effective design and optimization of intelligent radio systems. The outcomes of this analysis are instrumental in advancing the performance and reliability of communication systems, providing a significant contribution to the field of telecommunications. The investigation opens new avenues for research and development in the realm of intelligent radio systems, promising substantial improvements in the efficiency and effectiveness of signal processing and management.*

PROBLEM STATEMEN. Effective management of the correlation between signals within a cognitive radio system is crucial for overcoming challenges associated with interference. Correlation properties play a critical role in determining the network's ability to differentiate between various signals, thereby affecting overall efficiency. The development of new signal generation methods with enhanced resistance to interference is essential for addressing the difficulties arising from multiple access interference. Assessing the impact of signal energy and correlation properties on the resilience to cross-channel interference in cognitive radio systems enables the optimization of spectrum usage, the development of effective automatic interference detection and compensation mechanisms, which contribute to improved reception quality and ensure the reliable operation of the cognitive radio system under interference conditions.

INTRODUCTION

The objective of the article is to conduct an in-depth analysis of methods for assessing the impact of the energy and correlation properties of signals on their resistance to inter-channel interference in intelligent radio systems. The research focuses on discovering new methodologies for signal generation aimed at significantly improving spectrum efficiency and enhancing system resistance to interference. This includes analyzing the dynamics of energy characteristics and correlation impacts, and proposing innovative mechanisms for detecting and compensating for interference. The findings contribute significantly to the development and optimization of intelligent radio systems, improving productivity communication system productivity and reliability.

The research presented in the article is based on a comprehensive analysis of scientific publications by domestic and international scholars in the field of complex signal generation and optimization, as well as in the study of cognitive radio systems. Examination and analysis of works by authors [1-17] have allowed to deepen the understanding of the key factors that improve the resilience and efficiency of cognitive radio systems against interference. Specifically, Barker R.H.'s [1] work on sequences for secure communication has provided foundational insights into signal privacy and security. D'Amico A.A.'s [2] research into adaptive signal processing techniques has contributed to the development of more flexible and responsive cognitive radio systems. Furthermore, Lysechko V.P.'s [3-5, 9, 10] studies on spectral efficiency have highlighted the importance of optimizing signal transmission to maximize bandwidth usage without compromising signal quality. These contributions collectively offer a robust framework for advancing the field of intelligent radio communication, emphasizing the importance of continuous innovation and adaptation in signal generation and optimization strategies to meet the evolving demands of modern communication networks.

THE MAIN PART

To comprehensively assess the impact of multi-user access on the functioning of cognitive radio systems, it is essential to consider the effects of signal interaction, as well as their energy characteristics. Multiple access can affect system operation through conflicts and interference between signals transmitted by different users. This can lead to a decrease in the efficiency of information transmission and a deterioration in the quality of service. Cognitive radio systems, which are capable of adapting to changes in the frequency spectrum and selecting optimal data transmission paths, can mitigate these negative impacts.

It is also important to consider the energy aspects of signals in the context of multi-user access. High signal usage intensity can lead to an increase in energy consumption, which may be objectionable from the perspective of system sustainability and operating costs. Here, it is crucial to ensure a balance between the needs for high performance and rational energy use.

Inter-channel interference (ICI), also known as intersymbol interference or co-channel interference, occurs in communication systems when one signal in a channel creates disturbances for another signal in the same or an adjacent channel. This can happen under real-world conditions in the following scenarios.

1. Insufficient filtering. If filters do not effectively separate signals of different channels, signals can «spill over» from one channel into another.

2. Non-linearity in the transmission path. Non-linear components in the transmitter or receiver can distort the signal in such a way that its spectrum expands, encroaching upon adjacent channels.

3. Excessively high data transmission rates. At high data transmission rates, signals can overlap in time, leading to inter-channel interference, where the next symbol affects the current one.

4. Doppler shift in mobile systems. In mobile communication systems, where users are moving, Doppler shift can alter the frequency of a signal, potentially leading to channel overlap.

5. Lack of time synchronization. If signals from different channels are not synchronized in time, they can interfere with each other.

6. Effects of multipath transmission. In environments with multipath signal propagation (e.g., urban areas), reflected and scattered signals can arrive at the receiver at different times, creating interference.

7. Frequency overlap of channels. If adjacent channels do not have sufficient frequency separation, they can overlap, leading to inter-channel interference [1, p.206, 2, p. 2282].

8. Cross-modulation interference. This occurs when the modulation of one signal affects the modulation of another signal within the same or an adjacent channel. In complex communication systems, where multiple modulation schemes may coexist, the presence of a strong signal can modulate a weaker signal, altering its intended modulation pattern. This kind of interference is particularly challenging in dense spectral environments, where signals of varying strengths and modulation types are closely packed. Cross-modulation can lead to significant degradation in signal integrity, resulting in errors during demodulation and decoding processes, ultimately affecting the overall performance and reliability of the communication system. Identifying and addressing cross-modulation requires sophisticated signal processing techniques and adaptive modulation schemes to ensure that communication remains clear and reliable even in spectrally congested environments [5, p. 45, 8, p. 116].

9. Inter-channel interference and its causes are illustrated in Fig.1, representing a schematic of how inter-channel interference is generated. Grasping these issues is crucial for the design and implementation of robust communication systems capable of mitigating or avoiding the detrimental effects of ICI, thereby enhancing both the efficiency and reliability of data transmission across diverse environments and applications [3, p. 16, 12, p. 66].

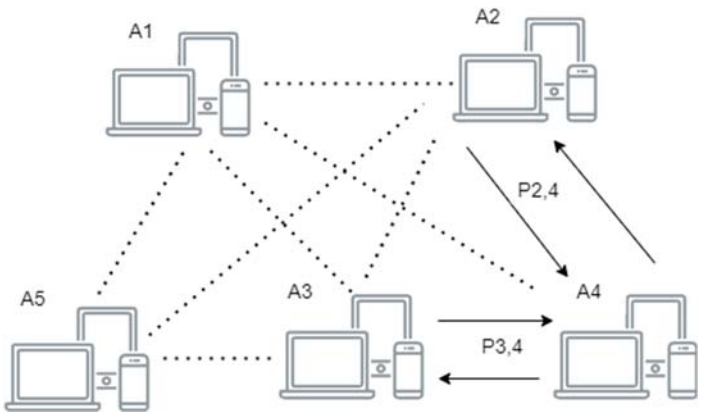

Fig.1. – Schematic illustration of inter-channel interference formation
(developed by the author`s)

The signal $P3{,}4$ is beneficial for subscriber $A3$, whereas the signals - $P3{,}5$ and $P1{,}3$ act as inter-channel interference. The signal $P2{,}4$ is beneficial for subscriber $A2$, while the signal - $P1{,}2$ serves as inter-channel interference. As an example, let's assume that the distance between subscribers $A1$ and $A2$, $A1$ and $A3$, $A3$ and $A4$, $A2$ and $A4$ is approximately equal, namely: $L1{,}2 \approx L1{,}3 \approx L3{,}4 \approx L2{,}4$.

By evaluating the distance at which the beneficial signal can be clearly separated from the inter-channel interference, and considering that the level of the antenna's side lobes does not exceed *0,1* $R_{\max}$.Where $R_{\max}$ is the maximum effective range within which a receiver can clearly distinguish a beneficial signal from interference. It is the limit at which signal strength remains sufficiently above the noise and interference levels for reliable communication

$R_{\max}$, we can disregard the impact of interference. Then we obtain a ratio $\log_2 \frac{L4{,}3}{L1{,}3} \cdot \frac{(2\ldots5)}{\sqrt{B}} = 0{,}1$, that allows determining the optimal distance between subscribers.

Where $\log$ – the logarithm function, which in this context is likely used to express the relationship between the strength of the beneficial signal and the strength of the interfering signals in a logarithmic scale, which is common in signal processing due to its ability to handle the wide range of signal strengths.

Assuming the base value B equals 20000, the ratio of distances $L1{,}2$ to $L1{,}3$, etc., varies within the range of *21,25* to *0,5*. Substituting values $R_{\max} \approx \frac{5}{\sqrt{B}}$, we get a distance of $L1{,}3$ = *11.3* km, and at the maximum value of $R_{\max} \approx \frac{2}{\sqrt{B}}$, the distance $L1{,}2$ is reduced to *6,7 km.* These calculations show that the minimum acceptable distance for differentiating the beneficial signal from inter-channel interference can vary significantly, which is unacceptable in modern communication systems. The impact of the antenna's directivity pattern on the level of inter-channel interference is substantial.

As can be seen from Figure 1, at the input of each subscriber's receiver, the sum of signals $\sum_{i=1}^{l_a} P_i(t)$ acts, where one is beneficial, that is, addressed to this subscriber, and the others $l_A - l = l_{Ich\_I}$ - are interfering, namely inter-channel interferences, under the condition that l_A>>1, meaning the interference is significant.

Based on the assessment of the system's parameters, it can be observed that it is necessary to take into account not only the receiver's own noise but also the inter-channel interference, which typically exceeds the impact of the receiver's own noise. The aggregate of signals can be considered normally distributed and stationary if the amount and character of the inter-channel interference are known and sufficient to apply the central limit theorem. In this case, the reception of a subscriber's addressed signal is conducted against the background of Gaussian noise, which serves as an approximation of the inter-channel interference [3, p.12, 4, p. 8].

The analysis of the resilience of intelligent systems to interference, including consideration of inter-channel interference, has allowed the construction of mathematical expressions for the quantitative description of the overall interaction of system elements. In the context of transmitting binary data through a common frequency range, denoted as ΔF and taking into account the number of active network participants, denoted as N_{act}, where $j = 1..l_{Ich\_I}$ $N_{act} = l_{act} - 1$, N_{act} =*{1,2,...,N}* and considering the individual power of each P_j signal creating interference, where *i* – is the index of each active subscriber apart from the one for which the measurement is being conducted (the signal power of this subscriber is not part of the interference for himself, therefore the index j in the sum should run all values from *1* до N_{act}, but not include *i*), the total interference power

P_{Ich_I} at the input stage of signal reception will be determined as follows [4, p.10-11]:

$$P_{Ich\_I} = \sum_{j=1, j \neq i}^{N_{act}} P_j . \qquad (1)$$

The spectral density of the power of inter-channel interference within the overall frequency band can be determined through the total interference power divided by the bandwidth. This density is an important parameter in analyzing the resilience of intelligent systems to interference and is defined as the average value of the interference power per unit of frequency [10 p. 279, 13, p. 216]:

$$S_{Ich\_I} = \frac{P_{Ich\_I}}{F} = \frac{1}{F} \sum_{j=1, j \neq i}^{N_{act}} P_j . \qquad (2)$$

To assess the quality of signal reception in the presence of inter-channel interference, it is necessary to calculate the Signal-to-Noise Ratio (SNR) in terms of the signal's energy E_i and the spectral density of the interference S_{Ich_I} In this case h^2 represents the square of the parameter that reflects the amplitude of the signal relative to the amplitude of the inter-channel interference, and E_i relates to the total energy of the signal that is received by the system. S_{Ich_I}, in turn, is the average power of inter-channel interference per unit of frequency in the spectrum [3, p.13, 9, p.102, 11, p.15]:

$$h^2 = \frac{2E_i}{S_{Ich\_I}} , \qquad (3)$$

For measuring the resilience of cognitive radio systems to interference, the Signal-to-interference ratio (SIR), also known as the signal-to-noise ratio (SNR) when referring to interference as noise, is a critical parameter as it determines the system's ability to distinguish the useful signal amidst noise and interference. A high SNR indicates that the signal is significantly stronger than the interference and noise, which implies that the system can process information more effectively.

Assuming that the interference between channels follows a normal distribution law, the resilience of a cognitive radio system against interference can be described using formula (4). If the duration of the signals is the same *(Ti = T)* and the power of the useful signal is $P_j = P_{avg}$, where P_{avg} – is the average power of the signal, then the energy of the signal E_i is determined as the product of P_j and *T* (the duration of the signal). Applying this definition of energy to formula (3), we obtain the following mathematical expression [10, p. 279, 15, p. 123]:

$$h^2 = \frac{E}{\sum_{j=1, j \neq i}^{Nact} E_i} . \qquad (4)$$

In cases where the power of the interfering signal P_{Ich_I} and that of the useful signal P_j are identical $P_{Ich\_I} = P_i$, the formula takes a form indicating that the system's robustness against interference is defined by the ratio of the signal's energy base B to the number of interfering subscriber signals. This means that the effectiveness of the system in countering interference depends significantly on its ability to manage and mitigate the effects of these competing signals, highlighting the critical role of signal energy foundation in enhancing communication reliability amidst potential disruptions [9, p. 103, 12, p.65]:

$$h^2 = \frac{B}{N_{Ich\_I}} = \frac{B}{N_{act} - 1} . \qquad (5)$$

In the field of cognitive radio systems, which are distinguished by their ability to adapt to changes in the radio frequency spectrum, a key indicator of performance is resistance to interference. This parameter measures the system's ability to maintain reliable communication despite the presence of unwanted signals. Assuming that inter-channel interferences are normally distributed, we can use the definition of the energy of the useful signal as shown in the image – $E = P_{avg} \cdot T$. When the power of the interference equals the power of the useful signal – P_{Ich_I} , this allows us to simplify the calculations and determine the ratio of the signal energy to the number of interfering signals. In other words, it evaluates how much the energy of the useful signal exceeds the total energy of the interferences.

An increase in the number of active subscribers N_{act} in a network usually leads to an increase in the level of inter-channel interference, and as a consequence, a decrease in the h^2 system's resistance to interference. To enhance interference resistance, one can increase the energy base B of the signals by expanding the frequency ΔF band and increasing the duration of the signal T_i. Thus, the spectral density of inter-channel interference $S_{Ich\_I} = {P_{Ich\_I}}/{F_i}$ is reduced due to the increase in signal energy.

However, these calculations do not take into account the intrinsic noise of the receiver. When including receiver noise as a normal stationary random process with a uniform spectral density of power S_0, the total spectral density of interference is determined as the sum $S = S_{Ich\_I} + S_0$ [3, p.13, 9, p. 104].

The ratio $h^2 = \frac{B}{N_{Ich\_I}}$ of the energy of the useful signal to its spectral density is an important parameter that aids in assessing the interference resistance under conditions where the power of the useful signal and that of subscriber signals are equal to each other. In this case, the height of the interference barrier h^2 is inversely proportional to the number of active subscribers and depends on the energy that the signal can accumulate (the energy base B), as well as on the base height of the barrier h_0^2, which is determined as the ratio of the useful signal's energy to the noise spectral density $h_0^2 = T$. The greater the signal's energy or the fewer the interferences and noise in the system, the higher the barrier, that is, the stronger the system's resistance to interference [9, p. 105, 7, p. 118]:

Adding to this content, it would be informative to discuss how this principle applies to various communication scenarios, such as in crowded urban areas versus rural settings where the number of interfering signals might be significantly different. It would also be valuable to consider the effects of advanced signal processing techniques that can improve the signal-to-noise ratio (SNR), such as spread spectrum technology or multiple-input multiple-output (MIMO) systems, which use multiple antennas to reduce the effect of interference and noise. Additionally, discussing the impact of regulatory constraints on frequency usage and power levels could provide a more comprehensive understanding of how interference resistance can be maximized within the given limitations.

$$h^2 = \frac{1}{\frac{N_{Ich\_I}}{B} + \frac{1}{h_0^2}}, \qquad (6)$$

However, this ratio cannot always be represented as a normal random process. In conditions where the number of active subscribers N_{act} is small and there is a significant difference in the levels of interfering signals, the normal distribution model may not reflect the actual level of inter-channel interference. In such scenarios, it is important to take into account the individual characteristics of each signal, the parameters of the system, and the operating conditions for an accurate assessment of interference resistance [8, p. 116, 16, p. 56].

Expanding on this, when dealing with a smaller number of subscribers and varying signal levels, other statistical models may be more representative of the interference, such as the Poisson distribution or even non-parametric models that make fewer assumptions about signal behavior. It's also critical to consider real-world factors such as terrain, building materials, and atmospheric conditions, all of which can affect signal propagation and interference. Techniques such as adaptive filtering, which dynamically adjusts to changing signal conditions, and cognitive radio technologies, which sense and adapt to the environment, can be particularly effective in such complex scenarios. Understanding these aspects is crucial for designing robust communication systems capable of operating efficiently in diverse and challenging environments.

Therefore, inter-channel interferences, which can be described using a normal stationary random process with a uniform spectral density, represent a specific model that only reflects a certain aspect of the operation of intelligent systems. Using this approach, we can only analyze the key parameters of the smart radio system. Namely: to estimate and compare the efficiency and resistance to interference, to determine the most effective modulation methods, to calculate the degree of interference protection under different conditions, and to choose the optimal ways of system synchronization in time and frequency. Such an approach opens the way to a deeper understanding and optimization of intelligent radio systems, ensuring higher efficiency of their operation, but it is not a universal approach.

The signal-to-inter-channel interference ratio at the receiver device input depends only on the signal base B, that is, it operates under the assumption that inter-channel interferences are normalized. It is important to consider that, in the analysis of an intelligent system, code division plays a significant role, which is based on differences in signal forms. In deriving the aforementioned formulas, certain assumptions were used, namely: all subscriber signals occupy the same frequency band with the same duration, and inter-channel interferences are considered as normal random processes with a uniform spectral density of power.

Such assumptions do not always reflect reality, because inter-channel interferences cannot always be represented as a normal random process with a uniform spectral density. Using expressions (2-6), it is possible to assess only the energy aspects of inter-channel interferences. This approach limits the analysis and evaluation and does not allow for a full consideration of the characteristics of complex signals [3, p. 13, 12, p.18]. Therefore, for a more accurate characterization of inter-channel interferences, a correlational approach should be used.

It's important to note that a correlational approach can capture temporal and spatial relationships within the signal structure that may be crucial for understanding and mitigating interferences. Furthermore, this approach can also facilitate the development of adaptive algorithms that dynamically adjust the receiver parameters in real-time to improve the signal-to-interference ratio, thus enhancing the overall robustness and reliability of the communication system.

To systematize the evaluation of the impact of inter-channel interference on the effectiveness of intelligent radio systems, a step-by-step algorithm has been proposed (table 1).

Let's examine the algorithm for assessing the impact of inter-channel interference in more detail.

In intelligent radio systems, the signal of each network user is a unique sequence that carries information and at the same time serves as an address code. This is achieved by encoding each bit of information in the form of a complex signal, the duration of which determines the subscriber's address. Thus, the signal of the j-th user can be expressed as a sum of modulated cosines, where each term of the sum corresponds to a separate bit of information, modulated at a certain frequency. Each bit of information is multiplied by a weighting coefficient $a_{j,k}$, which determines its contribution to the overall signal, and a delay kT_0, which ensures the correct positioning of the bit in time.

Table 1

Step-by-step algorithm for assessing the impact of interchannel interference

Step algorithm	Characteristic
1. Signal presentation	Each signal of the *j*-th user is represented as a sum of modulated cosine waves, where each element corresponds to a separate bit of information modulated at a specific frequency.
2. Modulation of information bits	Each bit of information is modulated by a weighting factor and a delay to ensure unique temporal positioning of the bit.
3. Description of the user signal	Mathematical description of the user's signal as a sum over all bits and signals transmitted in the network.
4. Accounting for multiple access	Taking into account the simultaneous operation of multiple subscribers, where each subscriber transmits their own signals that overlap in the spectrum.
5. Analysis of signals at the receiver input	Description of the signals at the receiver's input as sums of information signals, modulated and shifted in time.
6. Signal filtering	Utilization of a filter at the receiver, tuned to the specific signal of the subscriber, to separate the operational signal from interchannel interference.
7. Voltage value at the filter input	Calculation of the voltage at the output of the filter as a function of the autocorrelation or cross-correlation function of the signals.
8. Statistical analysis of signals	Analysis of the statistical properties of signals at the output of the matched filter, considering interchannel interference.
9. Signal/noise ratio	Determining the signal-to-interference ratio for different numbers of users in the system.
10. Efficiency analysis	Analysis of how increasing the number of users affects the efficiency of signal reception.
11. Development of refinement methods	Development and implementation of new signal processing methods and optimization of smart radio system parameters to enhance communication efficiency.

(developed by the author`s)

The cosine element with frequency $\frac{2\pi}{T_0}k$ ensures that each bit will be effectively modulated for transmission through the radio channel. Thus, mathematically, the signal $U_j(t)$ can be described by the expression [4, p. 11, 12, p. 17]:

$$U_j(t) = \sum_{k=1}^{N} U a_{\gamma(k)} U(t - kT_0) \cos\frac{2\pi}{T_0}\gamma(k)t \text{ . (7)}$$

This formula highlights the use of the Code Division Multiple Access (CDMA) method, where the use of different time delays and frequencies for each bit of information allows for multiplexing several signals within the same spectral range. Thanks to this approach, the intelligent radio system can simultaneously serve multiple users, increasing the efficiency of frequency resource use and providing high resistance to interference. This capability significantly enhances network capacity and reliability, enabling robust and efficient communication even in environments with high interference levels.

Formula (8) depicts the process of superposition (overlay) of signals from several subscribers in the Code Division Multiple Access (CDMA) system. It illustrates how the signal for each subscriber j consists of a sum of modulated cosines, including information symbols ξ_{kj}, which can take values depending on the bits of information being transmitted. Each signal is defined as a sum over all bits k and over all signals P_i currently being transmitted in the network. The factor $a_{j,k}$ represents the amplitude of each bit *k*, reflects the shape of the signal P_i considering delays in time for each bit and $U(t-kT_0-pT)$ signal, and the cosine function $\cos\frac{2\pi}{T_0}k(t-pT)$ with frequency represents the carrier for modulation. This demonstrates how CDMA technology enables multiple users to share the same bandwidth by assigning unique codes to each user, thus facilitating concurrent communication with minimal interference [5, p.47, 13, p. 118]:

$$\sum_{p}\xi_{pj}\sum_{k=1}^{N}Ua_{\gamma(k)}U(t-kT_0-pT)\cos\frac{2\pi}{T_0}\gamma(k)(t-pT) \cdot (8)$$

This model accounts for the possibility of simultaneous operation of subscribers N_{act} , where each subscriber can send their own signals that overlap in the spectrum. The distinction kT_0 pT in time delays for different bits and signals ensures unique addressing for each subscriber. Thus, signals from different subscribers can be separated from each other through correlation, despite their superposition in time and frequency.

Formula (9) describes the signal at the receiver's input in a multiple access system, where each subscriber transmits a signal continuously with a temporal shift. This mechanism allows for effective discrimination and decoding of signals from multiple users, leveraging the unique code patterns assigned to each to mitigate the effects of signal overlap [5, p. 50; 10, p. 112]:

$$U_{вх}(t)=\sum_{j=1}^{l}\sum_{p=-\infty}^{\infty}\xi_{pj}\sum_{k=1}^{N}Ua_{\gamma(k)}U(t-kT_0-pT\gamma_j)\cos\frac{2\pi}{T_0}\gamma(k)(t-pT-\gamma_j). \quad (9)$$

In such a system, the signal of each subscriber is a sum of information signals, modulated and time-shifted, which allows avoiding mutual interference when simultaneously using the same frequency resource. In this expression, the sum over *p* extends from minus infinity to plus infinity, reflecting the continuous operation of the system, and at each moment in time t, the receiver registers the superposition of signals from all active subscribers.

The time shift γ_j accounts for the delay in signals from different subscribers, which is crucial for ensuring proper synchronization and differentiation of signals in time. Each information symbol *ξkj* takes the value *±1*, depending on the information transmitted. This approach to signal transmission in intelligent radio systems allows not only for efficient use of spectral resources but also enhances communication reliability through the distribution of signals in time.

The receiver of the subscriber with number *m* is equipped with a filter that is tuned to the signal with the same number, referred to as signal *m* in formula (9), which acts as its operational signal. Signals coming from other subscribers are considered inter-channel interference, as they are not tuned to this filter. When the operational signal reaches the filter that is matched to it, the voltage at the filter's output becomes a function of the autocorrelation of the operational signal. In the case where an interfering signal with index *j (j ≠ m)* acts on the filter, the voltage will be determined by the cross-correlation function of the signals with indices *j* and *m*. Thus, the voltage at the output of the matched filter, assuming its presence at the input, will be expressed by the formula [9, p. 106, 12, p. 68]:

$$U_{вихj}(t)=a_{j,k}E_i\sum_{j=1}^{N_{акт}}\sum_{k=-\infty}^{\infty}\xi_{kj}R_{jm}(t-pT-\gamma_j)\times\cos\left[\frac{2\pi}{T_0}\gamma(k)(t-pT-\gamma_j)+\chi_{jm}(t-kT-\gamma_j)\right], \quad (10)$$

where $a_{j,k}$ – the constant that defines the gain coefficient of the filter;

E_i – the energy of the *i*-th signal;

$R_{jm}(t)$ – the function that describes the envelope of the cross-correlation function between the interfering signal with index *j* and the operational signal with index *m*;

$\chi_{jm}(t)$ – the phase of the cross-correlation function between the interfering signal with index j and the operational signal with index m.

In a generalized form, the envelope of the i-th signal can be described by the mathematical expression $\dot{U}_j(t) = U(t)\exp[i\theta(t) + ij\Delta\omega t]$,– thus, the function that describes the envelope of the cross-correlation function between the interfering signal with index j and the operational signal with index m will have the form [9, p. 107, 12, p. 69]:

$$R_{jm}(t) = \frac{1}{2E}\left|\int \dot{U}_j(\tau)^* U_m(\tau - t)d\tau\right| \cdot \qquad (11)$$

If the input signal is the main signal, that is, when $j = m$, under the condition that $R_{\max} = R(0) = 1$, then:

$$R_{mm}(t) = R(t) = \frac{1}{2E}\left|\int \dot{U}_m(\tau)^* U_m(\tau - t)d\tau\right| \quad .(12)$$

If in formulas (11), (12) the constant delay of the signal in the filter is ignored, since its value does not have a significant impact in this context, then the formula will take the form [11, p. 18; 14, p. 49]:

$$\begin{aligned} U_{jm}(t) = aE\sum_{j=1}^{l}\{&\xi_{pj}R_{jm}(t - pT - \gamma_j)\cos[\omega_0(t - pT - \gamma_j) + \chi_{jm}(t - pT - \gamma_j) + \\ &+ \xi_{p+1,j}R_{jm}(t - T - pT - \gamma_j)\cos[\omega_0(t - pT - \gamma_j) + \chi_{jm}(t - T - pT - \gamma_j)]]\}. \end{aligned} \qquad (13)$$

To determine the signal level with inter-channel interference using formulas (11 – 13), it is necessary to have information about the statistical properties of these signals at the output of the matched filter. Imagine a situation where the process of capturing information bits for the active user is precisely timed to occur at moments when the amplitudes of the maximum sidelobe bursts from the cross-correlation function reach their peak. This implies a scenario where sampling is optimized to coincide with these maximal amplitude instances, ensuring the most accurate data capture possible under given conditions. In such a case, disregarding the signal with inter-channel interference, the reference voltage will be equal to $\pm aE$, since $R_{\max} = 1$. The range of definition of the cross-correlation function (13) is *2T*, hence, at the sampling moment, the influence of two neighboring signals from each other subscriber in the sum should be considered, due to the overlap of their cross-correlation functions. Accordingly, by only keeping for each $j \neq m$ two closest terms in formula (13), can determine the level of the signal with inter-channel interference at the sampling moment $t = t_{ot}$ [11, p. 18; 14, p. 49].

The statistical characteristics of this sum in the universal case are determined by the envelope function R_{jm} and the phase χ_{jm} of the correlation function. If R_{jm} is a constant that does not change with the change of signal indices - $R_{jm} = r$, then the sum indicated in formula (11) transforms into a sum of sinusoidal waves with random phases at the outset, allowing it to be approximated by a normally distributed magnitude at the moment of counting, as indicated in (13). Furthermore, let's assume that the statistical properties of the sum are stationary, meaning they do not change over time.

Assuming that the mutual correlation characteristics of signals are identical, and for a perfectly correlated signal with minimal values R_{jm}, these magnitudes are the same in their amplitude $\frac{1}{\sqrt{\Delta FT}}$, as indicated in sources [9, 12]. The envelopes of real signals can have larger values, so to account for such situations, it is necessary to introduce a correction coefficient $\alpha \succ 1$. Therefore, the envelopes of the mutual correlation function R_{jm} do not change depending on the indices j, m and are constant [8, p.115]:

$$r = \frac{R_{jm}\alpha}{\sqrt{\Delta FT}}. \qquad (14)$$

The amplitude of each sinusoidal component with an envelope is represented by this symbol αEr. The distribution of inter-channel interference is approximated to a normally distributed random variable, and accordingly, its variance $\sigma^2_{Ich\_I}$, which reflects the signal power, is defined as [5, p. 52; 9, p. 103], where n is the number of terms in the sum:

$$\sigma^2_{Ich\_I} = \frac{n(aEr)^2}{2}, \qquad (15)$$

Considering that $n = 2(l-1)$ and assuming that l is significantly greater than 1, therefore $n \approx n-1$. By substituting the value of n in formula (15) taking into account expression, we obtain:

$$\sigma^2_{Ich\_I} = \frac{n(aE\alpha)^2}{2\Delta FT} \approx \frac{l(aE\alpha)^2}{\Delta FT}. \qquad (16)$$

Noise power level at the filter output [5, p. 52; 9, p. 103]:

$$\sigma^2_{Ich\_I} = \frac{a^2EN_{Sc}}{2}. \qquad (17)$$

Total interference power, which is the sum of internal device noise and inter-channel interference, will be equal to $\sigma^2 = \sigma^2_{Ich\_I} + \sigma^2_{Sc} = (a^2E/2)(S_{Ich\_I} + S_i)$, where according to equation (16), the spectral density of inter-channel interference is equivalent to $S_{Ich\_I} = \frac{2a^2lE}{\Delta FT}$. Therefore, the determination of the total spectral density of interference is:

$$S_0 = S_{Ich-I} + S_{Sc}. \qquad (18)$$

During coherent signal reception (where the receiver is phase-synchronized with the received signal, allowing for precise determination of the signal's amplitude and phase, thereby reducing the probability of errors during demodulation and decoding), the probability of error occurrence can be calculated using the following formula: [3, p.22; 10, p. 280]:

$$P = 0{,}5[1 - F(\eta h)], \qquad (19)$$

where – $F(x) = \sqrt{\frac{2}{\pi}}\int_0^x e^{-\frac{y^2}{2}}dy$ – probability distribution function for the standard normal random variable (Gaussian distribution);

$h = \sqrt{\frac{E}{S_0}}$ – square root of the signal-to-noise ratio calculated for error probability computation for various modulation schemes;

η – parameter varying depending on the chosen data transmission method. When using two opposite signals, $\eta = \sqrt{2}$

For cognitive radio systems, the spectral power S_0 can be calculated using formula. Thus, the signal-to-interference ratio is determined by the expression:

$$h^2_{\Sigma} = \left[\frac{\sqrt{B}}{\alpha_{max}\beta_{avr}(l_{act}-1)} + \frac{1}{E/S_0}\right]^{-1}. \qquad (20)$$

$$h^2_{Ich\_I} = \frac{\sqrt{B}}{\alpha_{max}\beta_{avr}(l_{act}-1)}, \qquad (21)$$

where $h^2_{Ich\_I}$ – SNR (Signal-to-Noise Ratio) at the receiver input;

$\beta_{avr} = \frac{1}{P_{use}(l_{act}-1)}\sum_{l=1}^{l_a-1} P_{nj}$ – the average level by which the noise exceeds the signal;

P_{use} – power of the useful signal;

P_{ij} – power of the interference signal;

a_{max} – the maximum value of the correction coefficient describing the cross-correlation characteristics of the signals.

Analysis of the dependency of the signal-to-interference ratio (S/I) at the input of the receiver's decision device for fixed values of the base and varying numbers of subscribers in the system showed that with an increase in the number of users, there is a significant decrease in the reception efficiency of the signal due to increased inter-channel interference.

The dependency of S/I (input data from Tabl. 2) for the number of users in the system, with changes $a = 1 - 5$.

Table 2

Calculation of the signal-to-interference ratio *(developed by the author`s)*

N_{act}	$a=1$	$a=2$	$a=3$	$a=4$	$a=5$
0	1,000	0,500	0,333	0,250	0,200
100	0,0995	0,0498	0,0332	0,0249	0,0199
200	0,0705	0,0353	0,0235	0,0176	0,0141
300	0,0576	0,0288	0,0192	0,0144	0,0115
400	0,0499	0,0250	0,0166	0.0125	0,0100
….	….	….	….	….	….
1000	0,031607	0,015803	0,010536	0,007902	0,006321

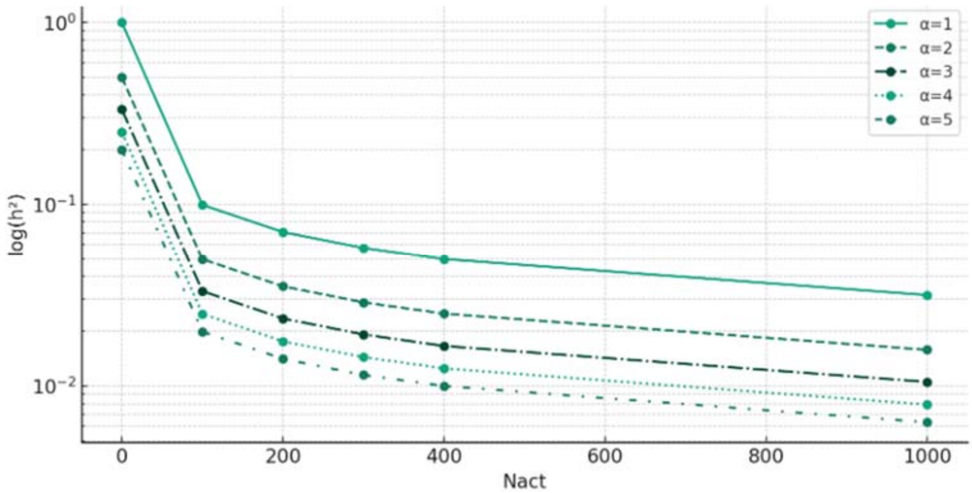

Fig. 2. Dependence of S/MZ on the number of users

CONCLUSIONS

A correlation between the deterioration of the mutual correlation properties of signals, which is reflected by the increase of the parameter *α,* and the decrease in the S/I (Signal-to-Interference) ratio has been identified. This result has significant practical importance, as it points to the necessity of developing ensembles of complex signals with improved mutual correlation characteristics for effective use in multiple access systems.

When considering the parameter as a constant, it's possible to derive a normalized relationship between the number of users, the noise level, and the allowable probability of error. This method enables the determination of optimal values based on calculated acceptable levels of the signal-to-interference (S/I) ratio, while also taking into account the signal's energy. By adopting such an approach, it becomes feasible to more precisely fine-tune system parameters. This leads to a reduction in errors and enhances the overall performance and efficiency of the communication system.

These results highlight the necessity for the development and implementation of new technologies and methods to increase the efficiency of multiple access systems, particularly through the improvement of mutual correlation properties of signals. Such improvements can significantly impact the throughput capacity of an intelligent system and the quality of radio communication, especially in complex data transmission conditions

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МЕТОДИ ЗА ОЦЕНКА НА ВЪЗДЕЙСТВИЕТО НА ЕНЕРГИЙНИТЕ И КОРЕЛАЦИОННИТЕ СВОЙСТВА НА СИГНАЛИТЕ ВЪРХУ УСТОЙЧИВОСТТА НА МЕЖДУКАНАЛНИ СМУЩЕНИЯ В ИНТЕЛИГЕНТНИТЕ РАДИОСИСТЕМИ

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Ключови думи: *Синтезирани сигнали, междуканална интерференция, корелационни ефекти, енергийни характеристики, когнитивни радиосистеми, методи за генериране на сигнали, методи за оптимизация.*

Резюме: *В статията се извършва задълбочен анализ на методите за оценка на влиянието на енергийните и корелационните свойства на сигналите върху тяхната устойчивост на междуканални смущения в рамките на интелигентни радиосистеми. Проучването е от ключово значение за идентифицирането на нови методологии за генериране на сигнали, целящи значително да подобри използването на спектъра и да се повиши устойчивостта на тези системи срещу смущения. Чрез сложната динамика на енергийните характеристики и корелационните ефекти, изследването предлага иновативни механизми за автоматично откриване и компенсиране на смущенията. Това изследване не само подчертава критичната необходимост от разглеждане на енергийните аспекти и предизвикателствата, породени от междуканалните смущения, но също така поставя основата за ефективно проектиране и оптимизиране на интелигентни радиосистеми. Резултатите от този анализ са инструмент за подобряване на производителността и надеждността на комуникационните системи, осигурявайки значителен принос в областта на телекомуникациите. Разследването отваря нови пътища за изследване и развитие в сферата на интелигентните радиосистеми, обещавайки значителни подобрения на ефективността при обработката и управлението на сигнали.*