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Methods for the Automatic Recognition of Digital Modulation of Signals in Cognitive Radio Systems

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Abstract—This paper considers one of the problematic issues of creating radio systems based on cognitive radio technology, viz., automatic recognition of the digital-modulation formats of radio signals. In accordance with the recommendations of the E2R and the European Telecommunications Standards Institute (ETSI) consortium, cognitive radio systems have the ability to modulate/demodulate signals in all frequency bands and in all modes of modulation. This process should be performed automatically, according to the current technical capabilities of the available communication system, the requirements for the quality of communication, and different external conditions. This article provides an analysis of the promising methods of automatic recognition of digitally modulated radio signal formats, viz., using the shape of the phase constellation, using the distribution difference of instantaneous phases, and using high-order cumulants. According to the results of the analysis, we propose methods of recognition that are based on cumulant analysis for cognitive radio systems. It is proposed that the decision-making device be an artificial neural network.

Keywords: cognitive radio system, digital modulations, recognition, artificial neural networks, cumulants.

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INTRODUCTION

To maintain high rates of development of telecommunication technologies and, in the wide sense, of the processing methods of weak broadband signals from noise, it is necessary to improve both the hardware, by raising the operating frequencies, as well as increasing its speed, performance and energy efficiency, and the mathematical methods of the processing of incoming data.

One of the perspective directions of the improvement of the hardware and software parts is the application of the methods of "cognitive signal processing," which allow receiving and using information about the current operating environment, dynamically and autonomously adjusting its parameters and protocols to achieve the preset purposes, and study of the obtained results. The main features of cognitive information technologies are the ability to extract and analyze information on the ambient radio space, to predict the changes in the communication channel, and to optimally adjust its internal parameters to adapt to the changes in the radio environment. In this case, recently, the arrangement of cognitive radio systems using a cognitive pilot channel (CPC) attracts great interest. The minimum sufficient information concerning the frequency bands, radio-access methods, services and state of the spectrum workload at the location of the terminal are passed through the CPC. In particular, it is assumed that radio systems that are created using cognitive signal processing methods [1] will:

– operate at all frequencies from 9 kHz to 300 GHz using narrowband control channels at the bandwidth less than 50 kHz as much as possible;

– receive, transmit and modulate/demodulate signal in all frequency bands and all modulation modes;

– have the ability to use programmatically defined readjustment of the inherent parameters.

The creation of circuitry that meets these strict requirements is possible owing to the use of extremely fast (with a clock frequency for the simplest devices of approximately 700 GHz) and energy-efficient electronics based on superconducting quantum interference devices (SQUID) [2–5].

In the development of the mathematical apparatus for cognitive signal processing the direction of the air monitoring mode that is the basis of the cognitive radio concept is particularly distinguished [6–8]. One important special problem of air monitoring is the development of methods for the automatic recognition of different modulation formats under conditions of prior uncertainty about the parameters of the received signals. Thus, in the telecommunication systems the choice of one of the many possible formats of signal modulation defines both the functional tasks of the radio communication system and the conditions of its operation.

The advanced methods for the automatic recognition of the format of digital modulation of the radio signal can be divided into three main groups according to the types of characters that are used for solving the problem: based on the form of the signal constellation; based on the structural characteristics of the signal; and using the statistical parameters of the signal. The purpose of this article is an analysis of the opportunities and definition of the problematic questions and development trends of the automatic recognition methods of digital modulation formats of radio signals in cognitive radio systems.

1. THE RECOGNITION METHODS OF THE FORMAT OF DIGITAL MODULATION RADIO SIGNAL BASED ON THE FORM OF THE CONSTELLATION DIAGRAM

Analysis of the current situation in world broadcasting shows that one of the most widespread format in the modulation of modern communication system is digital phase-shift keying (PSK). The main approach to the recognition of PSK signals is plotting constellation diagrams [9]. With this approach, the instantaneous angular signal phase and, consequently, the constellation diagram form or histograms of the instantaneous phase distribution are the informative characters. The recognition quality on the constellation diagram in many respects depends on the characteristics of the receiver and the quality of the communication channels (which one can characterize in a zero-order approximation using the signal-to-noise ratio (SNR) in the system). Therefore, the restoration of the constellation diagram, using, as a rule algorithms that are based on the "fuzzy c-means method" is the central problem of this approach [9]. These algorithms belong to the class of iterative clustering algorithms and allow recognition of signals with phase and amplitude-phase modulation (quadrature amplitude modulation (QAM)) with extremely low SNR values of up to 0 dB.

The limitation of this method is the need for synchronization with the carrier and clock frequencies, as well as the requirement of a priori knowledge of the maximum number of nodes of the constellation. In [10], the development of this method was proposed via the use of Kohonen self-organizing maps (KM), which is one of the options for the clustering of multidimensional vectors [11]. The advantage of the improved approach is the removal of the requirements for an a priori knowledge of the maximum number of the constellation nodes.

The development of methods of training based on Kohonen maps is a method of training with the nonparametric adaptation (parameter-less self-organizing map (PLSOM)). In [12] it was shown that the PLSOM algorithm provides greater training resistance than the classic algorithm of SOM (self-organized maps), owing to the weaker dependency of the number of clusters of the number of neurons in the map that are found by training.

In addition, to restore the constellation diagram of KM with the PLSOM training algorithm there is no need for a priori knowledge of the maximum number of clusters (the number of phase positions). In [10], it was shown that the algorithm provides the recognition of signals with digital phase modulation up to an SNR value of approximately 2 dB at the limit relative to detuning on the carrier frequency of the recorded radio signals ~ 10^{-3}. Note that for cognitive radio systems greater uncertainty on receiver synchronization is typical.

2. THE RECOGNITION METHODS OF THE MODULATION FORMAT ON THE DISTRIBUTION OF THE DIFFERENCE OF THE INSTANTANEOUS PHASES

In [13] it was proposed to recognize the signals with phase and frequency modulation (frequency-shift keying-FSK) via the use of the values of the difference of the instantaneous phase at the points and times nT and $(n-l)T$:

$$\Delta p(nT) = p(nT) - p((n-l)T), \qquad (1)$$

where the specific value of the index l is set by taking the maximum rate of change of the analyzed signal into account. For PSK signals upon a change in the value of the modulation parameter the peaks of the probability density function for the values $\Delta p(nT)$ will fall on the values 0, $\pi/2$, π, $3\pi/2$ (except that the PSK-4 signals shift at $\pi/4$). The described recognition method uses the behavioral features of a random process $\Delta p(nT)$, for which the parameter that most fully reflects the differences of recognizing aggregates is the value $x = \tau_1 / \tau_0$, where τ_0 is the residence time of random process $\Delta p(nT)$ within the interval $[\pi/4, 7\pi/4]$, τ_1 is the residence time of random process $\Delta p(nT)$ within the intervals $[3\pi/8, 5\pi/8]$, $[7\pi/8, 9\pi/8]$, $[11\pi/8, 13\pi/8]$.

For recognition of FSK and PSK signals the expression is used [13]:

$$p_1 = \frac{1}{N}\sum_{i=1}^{N} \psi_i^1(nT), \qquad (2)$$

where $\psi_i^1(nT) = 1$, if $\Delta p(nT) \in [3\pi/8, 5\pi/8] \cup [7\pi/8, 9\pi/8] \cup [11\pi/8, 13\pi/8]$, and $\psi_i^1(nT) = 0$ otherwise.

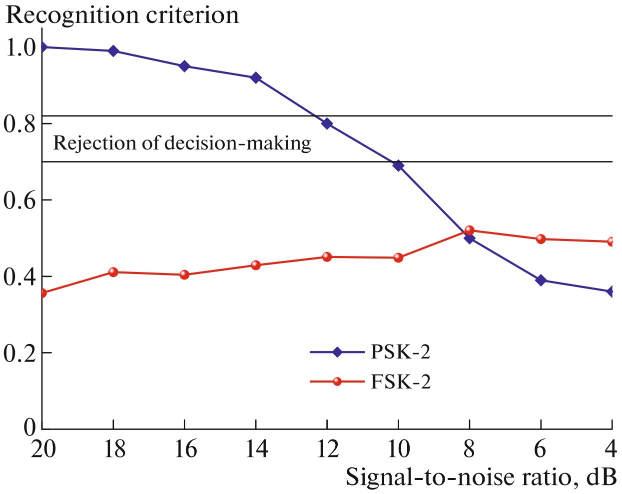

Fig. 1. The dependence of the PSK and FSK signal-recognition criterion on the SNR. Bottom: the dependence of the criterion for distinguishing the PSK-2 and PSK-4 signals on the SNR, dB (the PSK-2 digital modulation at the input).

The decision rule in this case is as follows:

$p_1 \geq 0.82 \rightarrow$ the "PSK signal" hypothesis is accepted;

$p_1 \leq 0.7 \rightarrow$ the "FSK signal" hypothesis is accepted;

$0.7 < p_1 < 0.82 \rightarrow$ no decision.

Similarly, the procedure for the recognition of the PSK-2 and PSK-4 signals is executed. Only expression (2) should be rewritten in the form:

$$p_2 = \frac{1}{N}\sum_{i=1}^{N}\psi_i^2(nT), \tag{3}$$

where $\psi_i^2(nT) = 1$, if $\Delta p(nT) \in [3\pi/4, 5\pi/4]$, and $\psi_i^2(nT) = 0$ otherwise.

The decision rule to recognize the PSK-2 and PSK-4 signals can be written as:

$p_2 \geq 0.66667 \rightarrow$ the "PSK-2 signal" hypothesis is accepted;

$p_2 < 0.66667 \rightarrow$ the "PSK-4 signal" hypothesis is accepted.

Summing the data for testing of these decision rules, one can conclude that the probability of correct recognition of the PSK-2 and 4-PSK signals is in the range of 0.95–0.98 (provided that the PSK signal is given to the input of the device).

The advantage of the considered approach is the absence of the need to synchronize the reception of signals with the carrier frequency. In particular, the method showed its efficiency under relative detuning on the carrier frequency from 1 to 1000 Hz (the sampling frequency of signal is 48 kHz, the symbol rate is 12 kbaud, and the number of samples is 1024). However, this method turned out to be sufficiently sensitive to the values of the SNR at the receipt of signal. Figure 1 shows the dependence that was calculated by authors of the coefficients p_1 (for PSK and FSK) and p_2 (for PSK-2 and PSK-4) that are included in the decision rules on the receiver characteristics and the quality of communication channels expressed through the signal-to-noise ratio relationship. The given experimental results show that the distinction of the PSK and FSK signals using the distribution of instantaneous phase difference is possible at an SNR of more than 12 dB and the distinction of the PSK-2 and PSK-4 signals is possible at an SNR of more than 8 dB. Taking the actual electromagnetic environment into account, whose complexity of depends on the location of radio-monitoring complexes in regions with a good infrastructure and large settlements, the achievement of such an SNR in real conditions is unlikely.

Thus, the main disadvantage of the distinction of PSK and FSK signals using the distribution of changes in instantaneous phases is the low noise immunity of the method. During an overlap of the additive noise on the PSK signal the appearance of the constellation diagram is distorted, in this case dependency of the constellation format on the noise intensity occurs, which blurs the probability density function peaks for the values $p(nT)$. As a result, at an increase in the noise intensity the distribution of a random process $p(nT)$ tends towards uniform distribution, resulting in signal-distinction errors.

3. THE RECOGNITION METHODS OF THE DIGITAL MODULATION FORMAT OF RADIO SIGNALS BASED ON STATISTICAL ATTRIBUTES

The article by E.E. Azzouz and A.K. Nandi [14], which was published in 1995, and a monograph by these authors [15] that was published 1 year later are among the classic works on the recognition of digital modulation formats of telecommunication signals based on statistical attributes. In these works, Azzouz and Nandi introduce a new system for the recognition of the attributes of the digital amplitude (ASK-2, -4), phase (PSK-2, -4), and frequency (FSK-2, -4) modulations of radio signals. The physical basis for using the system of attributes the specifics of the change in the instantaneous amplitude, phase, and frequency of the signal under different formats of modulation. The system is represented by a set of five recognition attributes, which are listed below.

1. The maximum value of the spectral power density of the normally centered instantaneous amplitude of the received signal is

$$\gamma_{\max} = \max|DFT(A_{cn}(i))|^2,$$

where $A_{cn}(i)$ is the value of the normal-centered instantaneous amplitude at the points of time $t = \frac{i}{f_s}$ ($i = 1, 2, \dots, N$), which is calculated as follows:

$$A_{cn}(i) = A_n(i) - 1,$$
$$A_n(i) = \frac{A(i)}{m_a},$$
$$m_a = \frac{1}{N}\sum_{i=1}^{N} A(i),$$

where $A(i)$ is the value of the instantaneous amplitude of the signal, N is the number of samples of the signal, and f_s is the sampling rate.

2. The standard deviation of the absolute value of the nonlinear centered component of the instantaneous phase is

$$\sigma_{ap} = \sqrt{\frac{1}{C}\left(\sum_{A_n(i)>a_t} \varphi_{NL}^2(i)\right) - \left(\frac{1}{C}\sum_{A_n(i)>a_t} \left|\varphi_{NL}(i)\right|\right)^2},$$

where $\varphi_{NL}(i)$ is the value of the nonlinear centered component of instantaneous phase and C is the number of samples of nonlinear phase components, i.e., the values of the instantaneous phase $\varphi(i)$ for which $A_n(i) > a_t$, a_t is the threshold value of $A_n(i)$.

The nonlinear component of the instantaneous phase means the value

$$\varphi_{NL}(i) = \varphi_{uw}(i) - \frac{2\pi f_c i}{f_s},$$

where $\varphi_{uw}(i)$ is the evolved instantaneous phase, and f_c is the carrier frequency.

3. The standard deviation of the centered nonlinear components of the direct instantaneous phase is

$$\sigma_{dp} = \sqrt{\frac{1}{C}\left(\sum_{A_n(i)>a_t} \varphi_{NL}^2(i)\right) - \left(\frac{1}{C}\sum_{A_n(i)>a_t} \varphi_{NL}(i)\right)^2}.$$

4. The standard deviation of the absolute value of the normal-centered instantaneous amplitude of signal is

$$\sigma_{aa} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} A_{cn}^2(i)\right) - \left(\frac{1}{N}\sum_{i=1}^{N} \left|A_{cn}(i)\right|\right)^2}.$$

5. The standard deviation of the absolute value of the normalized–centered instantaneous frequency is

$$\sigma_{fa} = \sqrt{\frac{1}{C}\left(\sum_{A_n(i)>a_t} f_N^2(i)\right) - \left(\frac{1}{c}\sum_{A_n(i)>a_t} \left|f_N(i)\right|\right)^2},$$

where

$$f_N(i) = \frac{f_m(i)}{r_b},$$
$$f_m(i) = f(i) - m_f,$$
$$m_f = \frac{1}{N}\sum_{i=1}^{N} f(i),$$

where $f(i)$ is the instantaneous frequency of the signal and r_b is the value of the bit rate.

The analysis of stability of this method to operate in real conditions showed that the method is workable at an SNR of more than 10 dB. At the relative detuning on the carrier frequency of a receiver of approximately 1%, a number of attributes that are associated with the phase and frequency information (σ_{ap}, σ_{fa}), lose their informativeness. Another disadvantage of this method is the incomplete number of recognized modulation formats that are used in modern telecommunication systems. In particular, there is no ability to recognize quadrature amplitude modulation (QAM).

The development of the "Azzouz and Nandi" technique is a method with a wide spectrum of recognized modulation formats (QAM-16 signals are included); it uses a number of additional recognition attributes, viz., the characteristics of the spread of the amplitude, phase, and frequency of the signal [16]:

$$R_a = \frac{m_a^2}{d_a}, \quad R_p = \frac{m_p^2}{d_p}, \quad R_f = \frac{m_f^2}{d_f},$$

where m_a, m_p, m_f are the average values of the instantaneous amplitude, phase, and frequency of the signal, respectively, and d_a, d_p, d_f are the dispersion of the instantaneous amplitude, phase, and frequency of the signal.

However, with the relative detuning of the receiver on the carrier frequency of approximately 1% the attributes R_p and R_f lose their informativeness.

Another modification of the "Azzouz and Nandi" method is a method that uses three new attributes for the recognition of the signal-modulation format [17]:

1. The logarithm of the dispersion of the absolute values of the instantaneous amplitude of the signal:

$$L\Delta_{aa}^2 = \log_{10}\left(\frac{1}{N}\left(\sum_{i=1}^{N} A_{cn}^2(i)\right) - \left(\frac{1}{N}\sum_{i=1}^{N}\left|A_{cn}(i)\right|\right)^2\right).$$

The attribute $L\Delta_{aa}^2$, which is due to logarithmic transformation that allows one to divide the ASK-2 and ASK-4 signals more effectively compared to σ_{aa}.

2. The box dimension.

We have a sequence of samples of the instantaneous amplitude signal: $a(1), a(2), \dots,$

$a(N), a(N+1)$. The box dimension is then calculated as

$$D(a) = 1 + \log_2 \frac{d(\Delta)}{d(2\Delta)},$$

where

$$d(\Delta) = \sum_{i=1}^{N} \left| a(i) - a(i+1) \right|,$$

$$d(2\Delta) = \sum_{i=1}^{N/2} \left(\max\{a(2i-1), a(2i), a(2i+1)\} - \min\{a(2i-1), a(2i), a(2i+1)\} \right).$$

The term "box dimension" in the above arguments is borrowed from the theory of fractals [18]. This attribute is proposed for use in order to distinguish the PSK-2 and PSK-4 signals.

3. The standard deviation of the absolute value of the evolved Instant phase [17].

$$\Delta_{ap} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} \varphi_{uw}^2(i)\right) - \left(\frac{1}{N}\sum_{i=1}^{N} \left|\varphi_{uw}(i)\right|\right)^2}.$$

In contrast to σ_{ap}, this attribute does not require one to know the exact value of the signal-carrier frequency to calculate the nonlinear components of the instantaneous phase. Δ_{ap} is used to distinguish the PSK and FSK signals. Obviously, under detuning of the carrier frequency of the receiver this characteristic loses its informativeness.

The original attributes that are used to distinguish the signal-modulation formats are the characteristics of the signal envelope. To calculate the characteristics the histograms of four kinds are plotted using the estimates of the signal power, P_s. A disadvantage of this method is the need to estimate the SNR preliminarily; for this the creation of sufficiently complicated measuring circuits it is required and the need to set the number of threshold values using an expert method.

4. THE THRESHOLD RECOGNITION METHOD OF FORMATS OF THE DIGITAL MODULATION OF SIGNALS USING HIGH-ORDER CUMULANTS

The methods that use cumulants as recognition atributes are a separate group of methods for the recognition of digital signal modulation formats. A distinctive feature of these attributes is the resistance to detuning on the carrier frequency at the solution of recognition problems.

A number of works [19, 20] have been devoted to the use of cumulants of various orders to recognize signal-modulation formats. Traditionally, the cumulant of a random variable is called the expansion coefficient of the logarithm of its characteristic function in the Maclaurin series:

$$\ln\theta(x) = \sum_{k=1}^{\infty} \frac{C_k (ix)^k}{k!}. \qquad (4)$$

The cumulants C_1, C_2, C_3, C_4 are the mean value, dispersion, asymmetry, and excesses of the random variable, respectively; the link between the cumulants and moments, M_k, of a random variable can be represented as:

$$M_1 = C_1, \quad M_2 = C_2 + C_1^2, \quad M_3 = C_3 + 3C_1C_2 + C_1^3.$$

The expansion of the logarithm of the characteristic function $\theta(x, y)$ for the aggregate of two random variables in a power series defines the cumulant of the two-dimensional probability distribution that describes the statistical links between the specified values:

$$\ln\theta(x, y) = \sum_{n,m=0}^{\infty} \frac{C_{nm}(ix)^n (iy)^m}{n!m!}, \qquad (5)$$

where the sum of the indices $n + m$ is the cumulant order C_{nm}. We also note that joint cumulants are cumulants for which both n and m differ from zero; for a two-dimensional Gaussian distribution only the cumulants of the first and second orders differ from zero in this case, while if all of the joint cumulants equal zero, then the random variables are statistically independent. The first joint cumulant, C_{11}, describes the correlation between the random variables.

The basic idea of the method for the recognition of modulation formats using higher-order cumulants can be formulated as follows:

the joint cumulants of a random complex variable and the values that are conjugated to it characterize the statistical links between a registered and mirror image distribution of the instantaneous phase of the signal.

In particular:

$$C_{2,2} = cum[x, x, \bar{x}, \bar{x}],$$

$$C_{2,2} = E_{2,2} - (E_{2,0})^2 - 2(E_{1,1})^2,$$

$$E_{2,2} = \frac{1}{N}\sum_{k=1}^{N}\left(x^2 \cdot (\bar{x})^2\right).$$

One can show that it is advisable to recognize some formats of modulation using the cumulants of the fourth order, while other formats should be recognized using comulants of the second order, etc. Figures 2, 3, and 4 show the distributions of the values of a number of cumulants for different formats of a modulation signal that were calculated by the authors. The synchronization of the analyzed signals with the carrier frequency was not performed; the SNR was 20 dB everywhere. The analysis results of these data show that

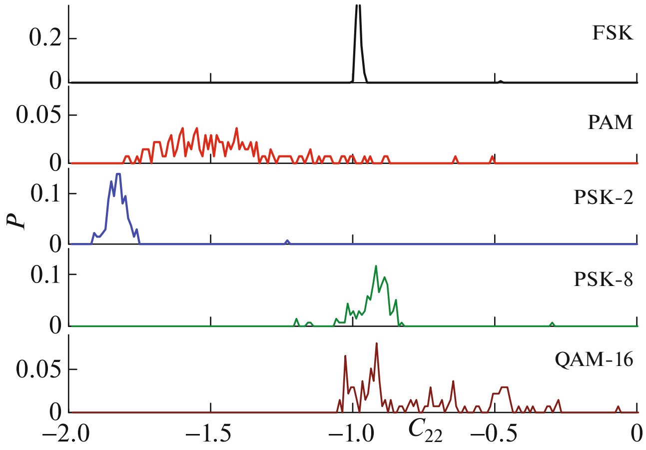

Fig. 2. The distribution laws of cumulant values for different signal-modulation formats.

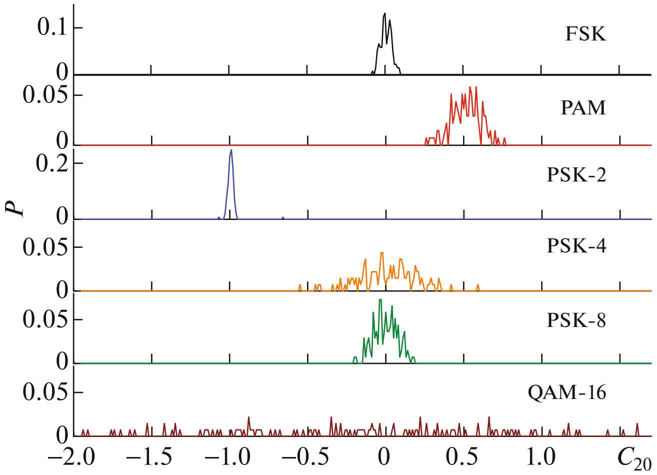

Fig. 3. The distribution laws of cumulant values for different signal-modulation formats.

using the cumulant C_{22} one can unambiguously select the FSK, PSK-2, and PAM (pulse amplitude modulation) signals; using the cumulant C_{20} the PSK-2, PAM, and QAM-16 signals can be selected, while using the cumulant C_{40} the PSK-2, PSK-4, and PAM signals can be selected. Thus, the solution of the problem of the recognition of the modulation formats using cumulants of higher-order requires one to select the corresponding cumulants and the specific rules for distinguishing them based on the results of the expert analysis of the cumulant values for different signal-modulation formats.

Let us consider some of the recognition methods of signal-modulation formats using high-order cumulants, which are the most interested from the point of view of the completeness of recognizing modulations. Among the methods, we believe it is reasonable to select a hierarchical scheme of the recognition of M-PSK, M-QAM, and M-PAM modulation formats [19]. The most successful method, as our simulation results show, recognizes four classes of signals, viz., PSK-8, QAM-16, PAM-4, and BPSK, using the decision rule where the criterion is the value of cumulant $|C_{40}|$:

$$\begin{array}{l} |C_{40}| < 0.34 \Rightarrow \text{PSK-8} \\ 0.34 \le |C_{40}| < 1.02 \Rightarrow \text{QAM-16} \\ 1.02 \le |C_{40}| < 1.68 \Rightarrow \text{PAM-4} \\ 1.68 < |C_{40}| \Rightarrow \text{BPSK} \end{array}. \qquad (6)$$

For the fourth class task at an SNR = 10 dB and a duration of the signal of 100 characters it correctly recognized over 95% of the samples. If we increase the signal duration to 250 characters, one can achieve almost entirely correct recognition of the PSK-8, QAM-16, PAM-4, and BPSK modulation formats. We studied the recognition method that was proposed in [19] for four modulation formats on the resistance to relative detuning of the carrier frequency. The numerical experiment was carried out for a signal duration of 250 characters at SNR = 20 dB; the relative detuning of the carrier frequency was approximately 8%. It turned out that the decision rule (6) with detuning on the carrier frequency does not allow one to distinguish the signals with PSK-8, 16-QAM, and BPSK modulation. The additional studies that the authors of this article performed allow the synthesis of a recognition algorithm for the PSK, QAM, and PAM signals. The algorithm that is shown in Fig. 5 is invariant to the quality of the receiver synchronization on the carrier frequency.

The disadvantage of the developed algorithm is the absence of a recognition set for frequency modulation (FSK), as the values of the cumulant, C_{22}, that were selected for use as a criterion of the decision rule for

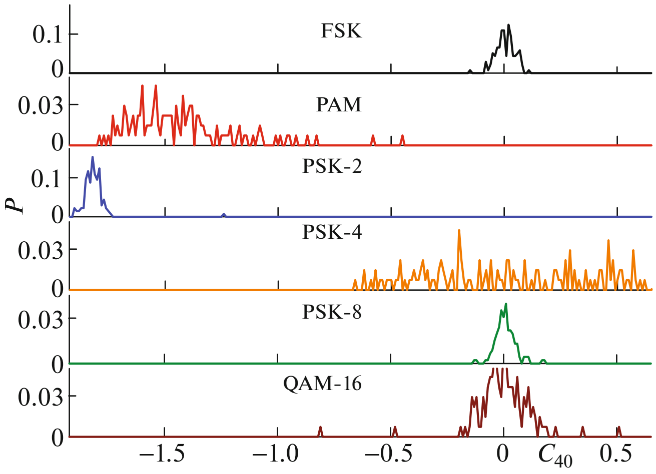

Fig. 4. The distribution laws of cumulant values for different signal modulation formats.

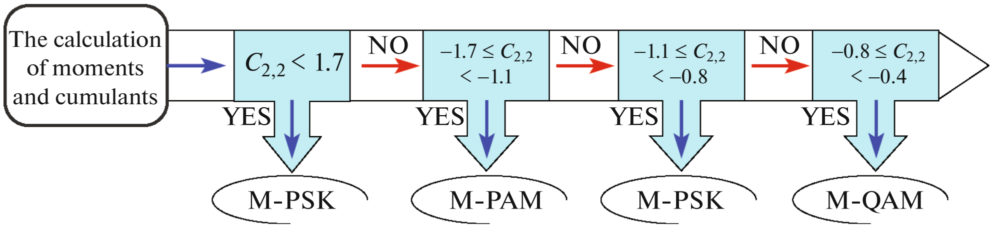

Fig. 5. An algorithm for the recognition of modulation formats that is invariant to the receiver synchronization of the carrier frequency of the signals.

FSK and PSK signals are in the same area. The solution to the problem of distinguishing FSK signals lies in the joint application of cumulant analysis and an estimation method for the distribution of the difference of the instantaneous phases. Using the cumulant C_{22} allows one to distinguish between the FSK signals and PSK signals of the PAM and QAM modulated signals. Further, based on the results that were presented in [19], of the general FSK and PSK class with the signals that use C_{40} and E_{20} it is possible to select the signals with PSK-8 modulation (the values of the indices for this format of modulation is close to zero). For the remaining mixture of FSK and PSK-2, 4 signals one can select the FSK-4 signals using the estimation method of the difference of the instantaneous phase distribution on criterion (2). Figure 6 presents an algorithm that permits one to distinguish the FSK signals from the signals of other modulation formats.

5. THE NEURAL NETWORK RECOGNITION OF SIGNAL MODULATION FORMATS USING HIGH-ORDER CUMULANTS

Different intelligent data-analysis methods, specifically artificial neural networks (ANNs), offer an alternative to the above methods for forming distinction rules (classification). The use of intelligent data-analysis methods to recognize the modulation formats of signals generally amounts to finding the informative recognition attributes and building a knowledge base (logical rules, decision trees and neural networks) based on the analysis of these attributes.

High efficiency of building separating surfaces in the multidimensional case is shown by ANNs as multilayer perceptrons. In accordance with the consequences of the Kolmogorov–Arnold–Hecht–Nielsen theorem, any multidimensional function of several variables can be represented using a two-layer neural network with direct complete association of a fixed dimension [22].

The neural network methods for the recognition of modulation formats [23, 24] differ from one another in the set of used recognition attributes and ANN parameters (the number of layers, the form of the activation function, etc.). Depending on the attribute set that is used, a trained ANN allows one to recognize a specific set of signal-modulation formats. In the present case, the task of the researcher is the optimization of the ANN structure for the most effective recognition (with the required probability of a correct solution) of a given set of digital signal-modulation formats. The action sequence for creating the neural network device of the recognition of modulation formats

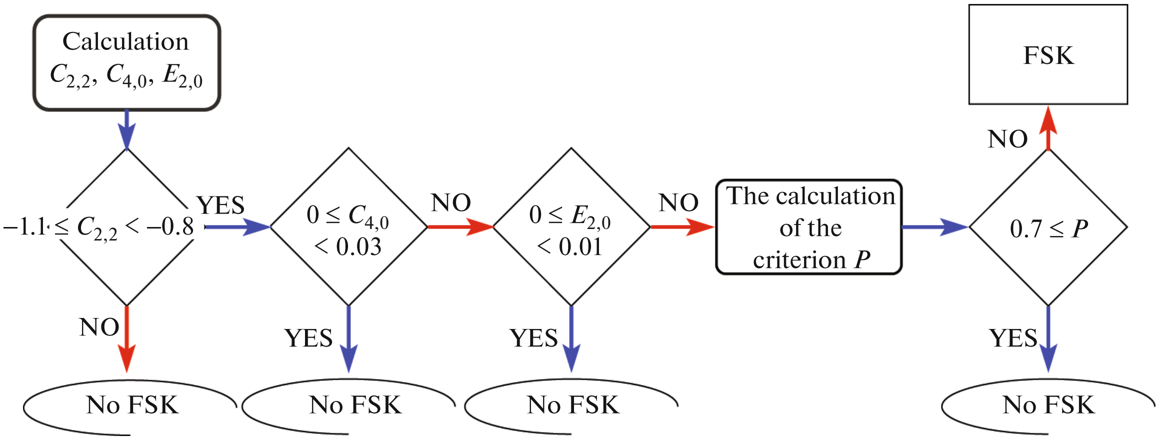

Fig. 6. An algorithm for distinguishing FSK signals.

in cognitive radio system can be represented as the following stages.

The neural network recognition of modulation formats using statistical recognition attributes, including cumulants, that was optimized by authors can be described using the following sequence [25–27].

Stage 1. Based on a given set of the modulation formats $T = (T_1, T_2, ..., T_n)$ that must be recognized, the analysis of the informative attributes $C = (C_1, C_2, ..., C_m)$ by which it is possible to recognize these modulation formats is performed.

Stage 2. The analysis of the limitations of the problem solution is provided with the signal-propagation environments and receiver–transmitter parameters, viz., the interference, limiting SNR, synchronization quality, etc. $V = (V_1, V_2, ..., V_k)$.

Stage 3. Taking the obtained limitations into account, V, the applicability of the selected attributes of recognition, C, is analyzed, i.e.,

$$(C_1, C_2, \dots, C_m) \xrightarrow{V} (C_1, C_2, \dots, C_l), \quad m \geq l. .$$

Stage 4. Taking the number of recognition attributes l and types of recognition n into account ANN with the parameters $H = (l, n, \{Ns\}, \{Tr\})$ is formed, where l is the number of inputs (this corresponds to the number of recognition attributes), n is the number of outputs of the ANN (this corresponds to the number of recognizing modulation formats), $\{Ns\}$ is neural network parameters (the number of layers, the number of neurons in each layer, the form of the activation function, etc.), $\{Tr\}$ is the training parameters of ANN (training algorithm, the maximum number of training cycles, the criterion of shutdown training, etc.).

Stage 5. The training of the ANN is performed. Based on the training results the correction of the parameters $\{Ns\}$ and $\{Tr\}$ is possible. Based the results of training and correction the final ANN for recognition of modulation formats is formed. The analysis of the simulated results shows that a previously trained multilayer perceptron provides the probability of the correct recognition of signal modulation: FSK-2 approximately 0.99, PAM ~ 0.98, PSK-2 ~ 0.99, PSK-4 ~ 0.7, PSK-8 ~ 0.98, and QAM-16 ~ 0.86 at SNR ~ 20 dB. The low probability of the recognition of PSK-4 signals is due to the rather strong intersection of distribution laws that are used as attributes for PSK-4 signals and PSK-8 signals (as shown in Figs. 2, 4). If the authentication of PSK-4 signals and PSK-8 signals is not considered as an error, then the probability of correct recognition of a PSK-4 signal is ~ 0.83.

6. CONCLUSIONS

Analysis of different approaches to the automatic recognition of modulation formats showed that with prior uncertainty of the receiving signal parameters the methods that are based on cumulant analysis are the most effective way to determine the modulation format. The advantage of this approach is a broad class of recognized digital modulation formats and the absence of the need for high-precision reception synchronization on the signal-carrier frequency. Using an artificial neural network as a decision device allows one to consider the actual electromagnetic environment at the location of the operation of a cognitive radio communication system at the stage of training via the use of training samples of signals with the corresponding SNR. Further development of the cumulant methods for the recognition of digital modulation formats of radio signals and their applicability to cognitive radio systems can be studied by separating the properties of higher-order cumulants and their integration with other informative recognition attributes of modulation formats.

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