Radioelectronic and Computer Systems, 2022, no. 4(104)
ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 621.391.8:311.218
doi: 10.32620/reks.2022.4.08

Mykola BUHAIOV[1], Volodymyr KLIAZNYKA[1], Ihor KOZYURA[1], Denys ZAVHORODNII[2]

[1] *Zhytomyr Military Institute of S. P. Korolev, Zhytomyr, Ukraine*
[2] *Navy Institute National University «Odessa Maritime Academy», Odessa, Ukraine*

METHOD FOR SPECTRUM HOLES DETECTION BASED ON MODE ANALYSIS OF SPECTRAL SAMPLES HISTOGRAM

*The **subject** of this article is the process of detection and estimation frequency boundaries of spectrum holes under conditions of high spectrum occupancy when using receivers with narrow instantaneous bandwidths. The work **increases** the probability of spectrum holes correct detection in conditions of high occupancy of the radio frequency spectrum and variable noise levels by developing a method to distinguish signal and noise samples based on the analysis of the histogram of spectral sample modes. The **tasks** to be solved are: development of a method for separation signal and noise samples in the frequency domain; development of a methodology to find the minimum mode of a multimodal probability distribution; determination of frequency boundaries of spectrum holes; formulation of recommendations for the practical implementation of developed method. The **methods** used are: methods of probability theory and mathematical statistics, methods of statistical modeling. The **essence** of the proposed method is to distinguish the set of energy spectrum samples using a threshold, obtained for the value of the histogram mode, which corresponds to noise, and to determine the frequency boundaries of spectrum holes. The following **results** were obtained: an expression for calculating the threshold value for separation signal and noise samples in the frequency domain using the value, which corresponds to the noise mode of the frequency samples of the probability density function. It was found that the noise mode has the smallest value among other modes, since noise samples have a smaller value compared to the signal ones. A technique for estimating the value of the noise mode has been developed, which consists of a histogram of energy spectrum frequency samples and finding the partition interval that corresponds to the value of the minimal mode. An approach was proposed to determine the frequency boundaries of noise samples in the presence of one signal in the analyzed band. **Conclusions.** The developed method allows detecting spectrum holes with a probability of at least 0.9 at signal-to-noise ratio values of at least 5 dB for the spectrum with a rectangular shape envelope and 12 dB for other envelopes under occupancy of up to 80%.*

***Keywords:** histogram; mode; spectrum occupancy; test statistics; spectrum hole; Welch periodogram.*

Introduction

Rapid development of Internet of Things technology and wireless sensor networks [1-3] creates a shortage of radio frequency resources. This is primarily due to a significant increase in the number of radio-electronic devices and, as a result, an increase in occupancy of radio frequency spectrum (RFS) and complication of radio signals time-frequency structure [4]. To solve this problem, the technology of cognitive radio is used [5]. The basis of cognitive radio systems is dynamic use of RFS by means of continuous control of spectrum occupancy [6, 7]. Method of spectrum holes detection proposed in [8] becomes unstable and cannot be used in the conditions of an unknown level of spectrum occupancy when analyzed frequency band is occupied more than 60 %.

In recent years, a significant number of publications have been devoted to the issue of spectrum holes detection. In particular, in [9], to solve the problem of detecting unoccupied frequency channels in cognitive radio networks, it is proposed to use algorithms for evaluation changes in the statistical properties of signals. In [10], a method for detection free channels in RFS using spectral correlation functions and convolutional neural networks is proposed. In [11], an energy detector with an adaptive threshold is proposed, which provides improved characteristics in conditions of unknown noise level.

An improved energy detector was proposed in [12, 13] to detect unoccupied frequency channels. It is shown in [14] that the application of a machine learning algorithm of random forest type provides an accuracy of about 91 % in determination of free areas of RFS. A wide-band energy algorithm for the detection of unoccupied frequency channels is proposed in [15]. A two-stage energy detector is proposed in [16]. In [17], a detector that combines an energy detector and a matched filter is used to detect spectrum holes. In [18], a method for determining unoccupied regions of RFS in conditions of changing their bandwidth using order statistics was developed.

A general drawback of existing methods for spectrum holes search is low probability of their correct detection in conditions of high RFS occupancy and variable noise level, which is a characteristic feature of modern radio electronic environment in places with a high density of electronic devices.

This leads to the contradiction that the cognitive radio technology requires reliable and stable methods of detecting spectrum holes, and existing approaches are not able to solve this problem.

Therefore, the aim of this article is to increase the probability of correct spectrum holes detection in conditions of its high occupancy and variable noise level by developing a method for separating signal and noise samples based on the analysis of histogram of spectral samples modes.

1. Method of signal and noise samples distinguishing based on mode histogram analysis

When developing method foe spectrum holes detection, we will rely on the following initial conditions: the width of signal spectrum and its shape are unknown, the noise level is also unknown and may vary over time. It is also assumed that the noise level is the same for all frequency samples in analyzed frequency band.

At the same time, all possible envelope shapes of signal energy spectrum we divide into two categories: an almost rectangular envelope shape, which is characteristic of OFDM signals, and other envelope shapes. In course of research, it was established that for the first case, the probability density function (PDF) of frequency samples of a signal and noise mixture can be bimodal (one signal and one noise mode). In the second case, the PDF always has one mode that corresponds to noise samples. Degree of signal mode manifestation depends on the value of the signal-to-noise ratio (SNR) and the relative width of signal spectrum.

The essence of the proposed method consists in dividing the set of frequency samples of energy spectrum into signal and noise ones using threshold, obtained for the value of noise mode of frequency samples histogram, and determining frequency boundaries of free frequency channels.

Energy spectrum of the received signal is calculated using Welch periodogram. Length of the analyzed sequence is N samples, length of the fast Fourier transform (FFT) window is N_{FFT} and the overlap between windows is R samples.

Then the PDF of noise frequency samples is subject to a χ_k^2 distribution with $k=(N-N_{FFT})/R+1$ degrees of freedom.

The value of noise mode for χ_k^2 distribution is related to the unknown value of the noise variance σ_ξ^2 by the following equation [19]:

$$m=\sigma_\xi^2(k-2)\,. \tag{1}$$

Then the threshold using the Wilson-Hilferty approximation [19] of χ_k^2 distribution for the probability of false alarm P_F, taking into account the expression (1), can be calculated by the following expression:

$$\gamma=\frac{k\cdot m}{k-2}\left(1-\frac{2}{9k}+u_p\sqrt{\frac{2}{9k}}\right)^3, \tag{2}$$

where

$$u_p=4{,}91\left(p^{0{,}14}-(1-p)^{0{,}14}\right),\ p=1-P_F\,. \tag{3}$$

Therefore, the task of distinguishing signal and noise samples in frequency domain consists in finding the value of noise mode and calculating the threshold value according to expression (2). Since noise samples have smaller values compared to signal samples, noise samples will always have the lowest mode value.

2. Search of minimal mode of multinomial distribution

Method of finding the mode of PDF for noise consists in calculation a histogram of energy spectrum frequency samples and finding the division interval that corresponds to the value of minimum mode. The accuracy of mode value estimates depends on number of accumulated realizations of energy spectrum and histogram parameters. The number of power spectral density samples, based on which the histogram is calculated, is $M=N_{FFT}k$. It is recommended to choose the number of intervals for dividing frequency samples equal to $d\approx N_{FFT}$.

In case of an almost rectangular signal spectrum shape envelope, the PDF of frequency samples will be multimodal, and the value of PDF for the noise mode at high frequency band occupancy η may be less than for the signal mode. For signals with other shapes of spectrum envelope, the PDF of frequency samples will have one mode and the noise mode will correspond to the maximum of frequency samples PDF. Therefore, the procedure to search the value of noise mode consists in estimation the histogram of frequency samples, calculation

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

some statistics of histogram and comparing it with the threshold for determining the type of PDF.

During experimental researches, it was established that the best separation of unimodal and multimodal types of PDF for all values of spectrum occupancy and SNR is achieved when using kurtosis as a test statistic. In fig. 1 is shown the dependence of the kurtosis via SNR of histograms for signal frequency samples with phase shift keying (PSK) and orthogonal frequency division multiplexing (OFDM) signal at frequency band occupancy of about 80%. A kurtosis value of less than 6 (threshold) indicates that there is a signal with a rectangular spectrum envelope in received signal mixture, and value of the SNR does not exceed 12 dB. In this case, the minimum mode value is determined for a smoothed histogram using a moving average window. Otherwise, the value is determined for the histogram without smoothing.

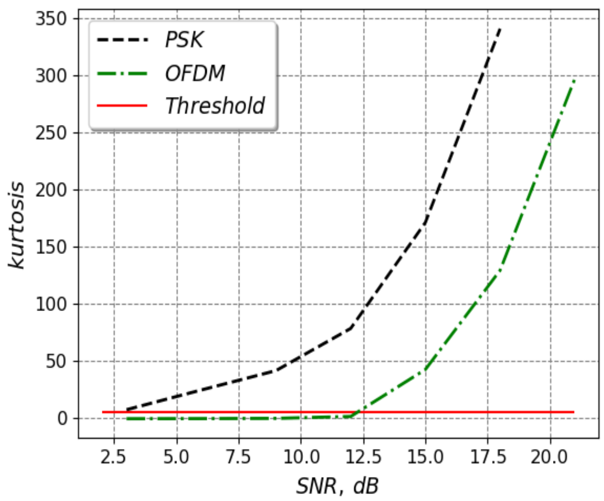

Fig. 1. Dependency of histogram kurtosis via SNR

The error of false alarm probability estimation, even for the same threshold calculation error, will be different for different values of P_F. Therefore, as a characteristic of the proposed method, we will choose the relative error of estimation the mode value for noise ε_m. In fig. 2 is shown dependence of relative error of estimation noise mode via SNR for different types of spectrum envelope and band occupancy. This error determines the error in calculation of threshold γ for distinguishing noise and signal frequency samples.

As SNR increases, the growth of ε_m can be explained by the fact that the fragment of histogram, which corresponds to noise, is represented by a smaller number of partition intervals. However, in spite of such, at first glance, large values of error for determining spectrum holes will be carried out correctly, since relative value of the noise power will be small and will have an insignificant effect on the threshold γ. A negative result of large ε_m values will be a decreasing of dynamic range, which will lead to the fact that weak signals will not be detected.

The above considerations will be fair for $k > 2$. When $k = 2$ PDF of noise degenerates into an exponential one, for which $m = 0$ and in this case, it is necessary to develop other approaches to distinguish signal and noise samples. However, with small values of k, the spectrum will have significant fluctuations, which will make it difficult to determine spectrum holes frequency boundaries, and this case was not considered in this paper.

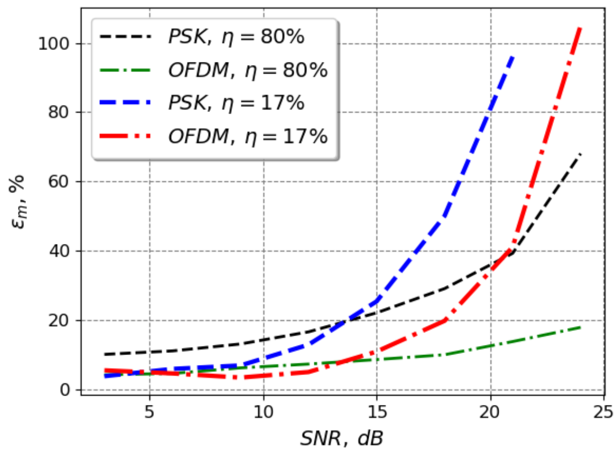

Fig. 2. Dependency of noise mode estimate relative error via SNR

3. Search of spectrum holes boundaries

Spectrum holes search was carried out under the assumption that only one signal is present in analyzed frequency band. Due to significant fluctuations of signal spectrum envelope at small k values, as well as at high P_F values, a significant number of non-adjacent frequency samples may exceed the threshold calculated using expression (2). In this case, as a result of automatic search for spectrum holes, a significant number of them may be detected. For energy spectrum frequency samples $P_{xx}(i)$, where $i \in [0, N_{FFT}]$ – are their numbers, positions of noise samples can be found using following expression:

$$i_\xi = \arg(P_{xx}(i) < \gamma). \quad (4)$$

Then, depending on signal spectrum position relative to the bandwidth of receiver (adjacent to the right or to the left to its border or located in center), spectrum holes Π_ξ can be detected using such equations:

$$\Pi_{\xi} \in \left[0, i\left(B_0\right)\right], \left[i\left(B_0+1\right), N_{FFT}\right),\ 0 < B_0 < \max\left(i_{\xi}\right)$$
$$\Pi_{\xi} \in \left[i\left(B_0\right), N_{FFT}\right),\ B_0 = 0, \qquad (5)$$
$$\Pi_{\xi} \in \left[0, i\left(B_0\right)\right],\ B_0 = \max\left(i_{\xi}\right),$$

where

$$B_0 = \operatorname{argmax}\left(\operatorname{diff}\left(i_{\xi}\right)\right). \qquad (6)$$

If there are several signals in analyzed frequency band, then as a result of the proposed method, only signal with the widest spectrum will be detected. The remaining regions of RFS will be defined as spectrum holes.

4. Study of developed method

Developed method was studied for the following values of Welch periodogram parameters: $N_{FFT} = 1024$, $R = 512$, $k = 30$, $N = 15872$, type of window function – Hamming. We fix the probability of a false alarm at the level of $P_F = 0,1$. Number of realizations of energy spectrum, according to which the histogram is calculated, was chosen equal to $k = 50$.

For each type of spectrum shape envelope, occupancy levels of about 80% and 20% at 3 dB and 20 dB SNR were considered for each of them.

Fig. 3,a shows detected spectrum holes (green colored) for analyzed RFS area with an OFDM signal at high spectrum occupancy (more than 80%) and the corresponding histogram (b) at a low SNR. Detected spectrum holes for high SNR (20 dB) are shown in fig. 3,c. In the upper right part of fig. 3,d, as well as the corresponding figs. 4-6, a fragment of the histogram for noise samples is shown on an enlarged scale.

Fig. 4 shows similar pictures for spectrum occupancy of about 20 %. From these figures, it can be seen that at high SNR area of the histogram that corresponds to noise samples is represented by a small number of intervals, which worsens the accuracy of noise mode estimate. Moreover, with low occupancy level, the error will be greater.

Figs. 5-6 show similar graphs for the case of placement in analyzed frequency band of one PSK signal with different spectrum widths and with different values of SNR.

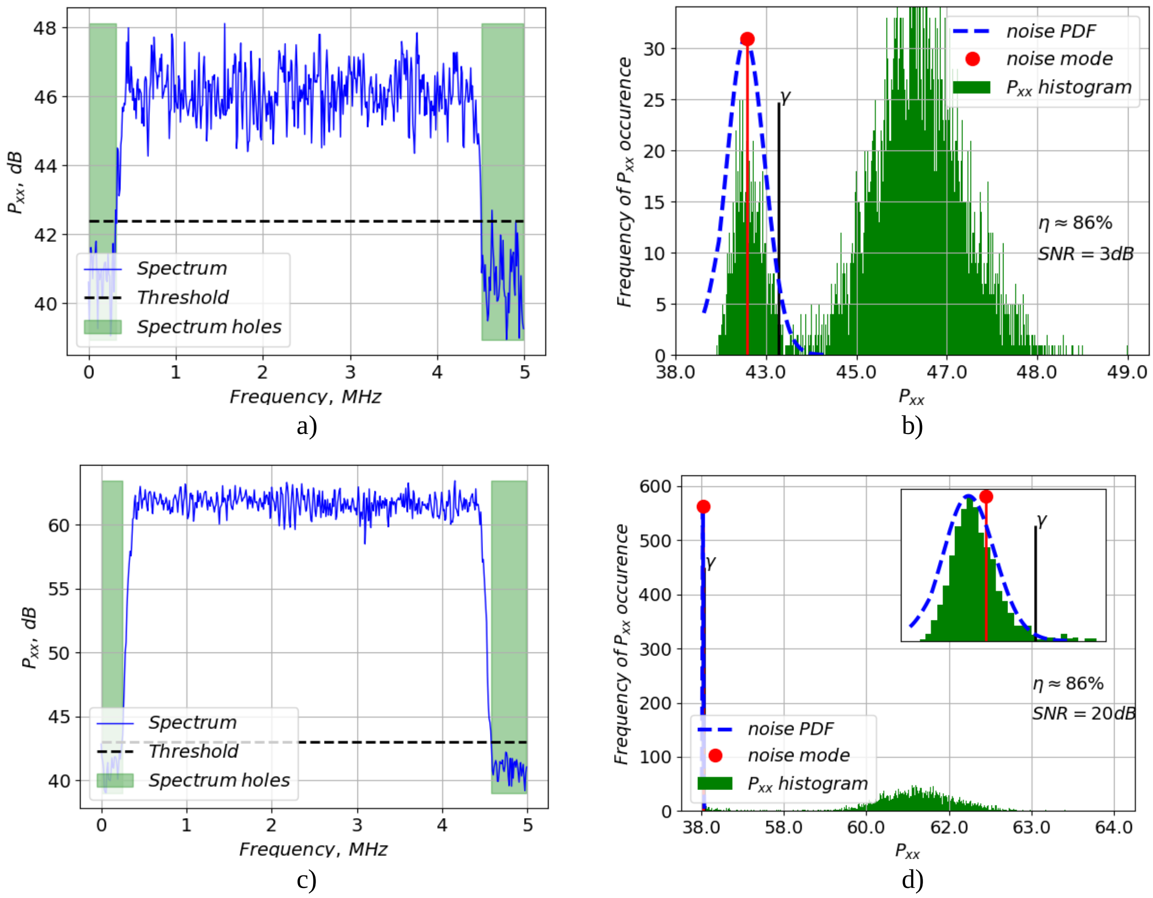

Fig. 3. Spectrum holes for RFS with OFDM signal (a, c) and corresponding histograms (b, d) for high spectrum occupancy

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

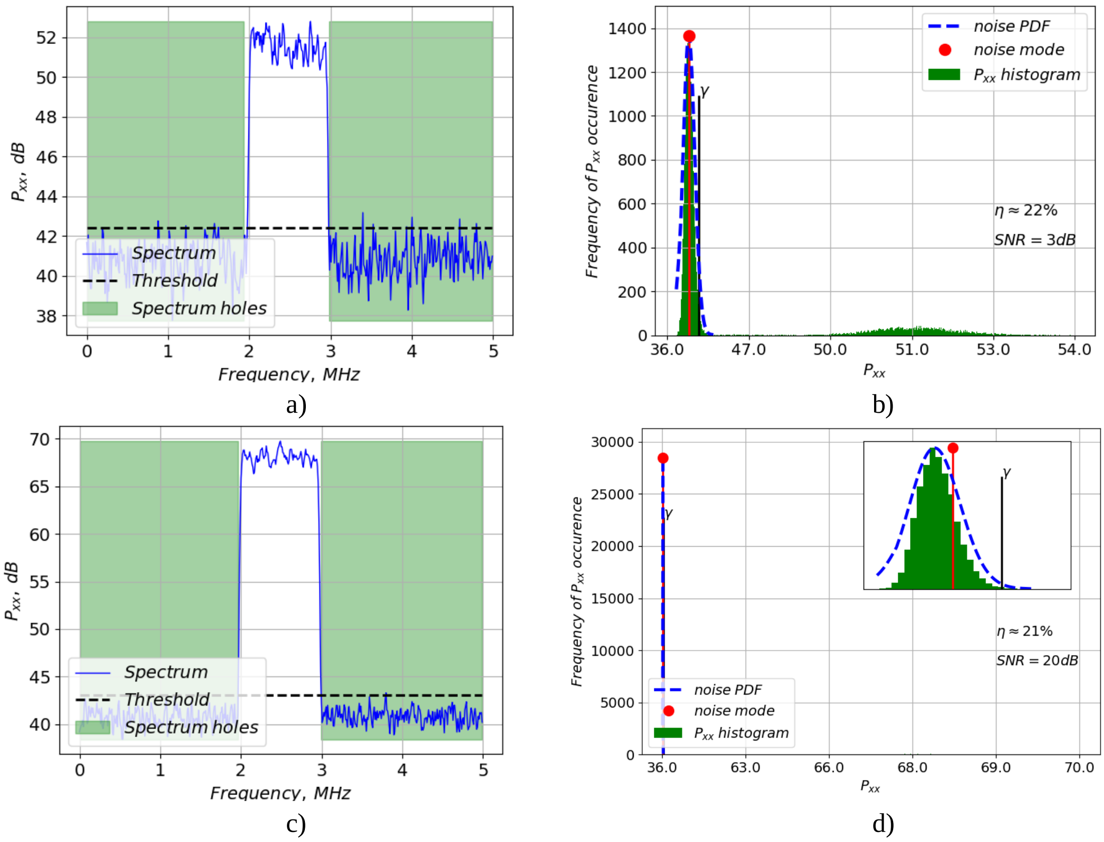

Fig. 4. Spectrum holes for RFS with OFDM signal (a, c)
and corresponding histograms (b, d) for low spectrum occupancy

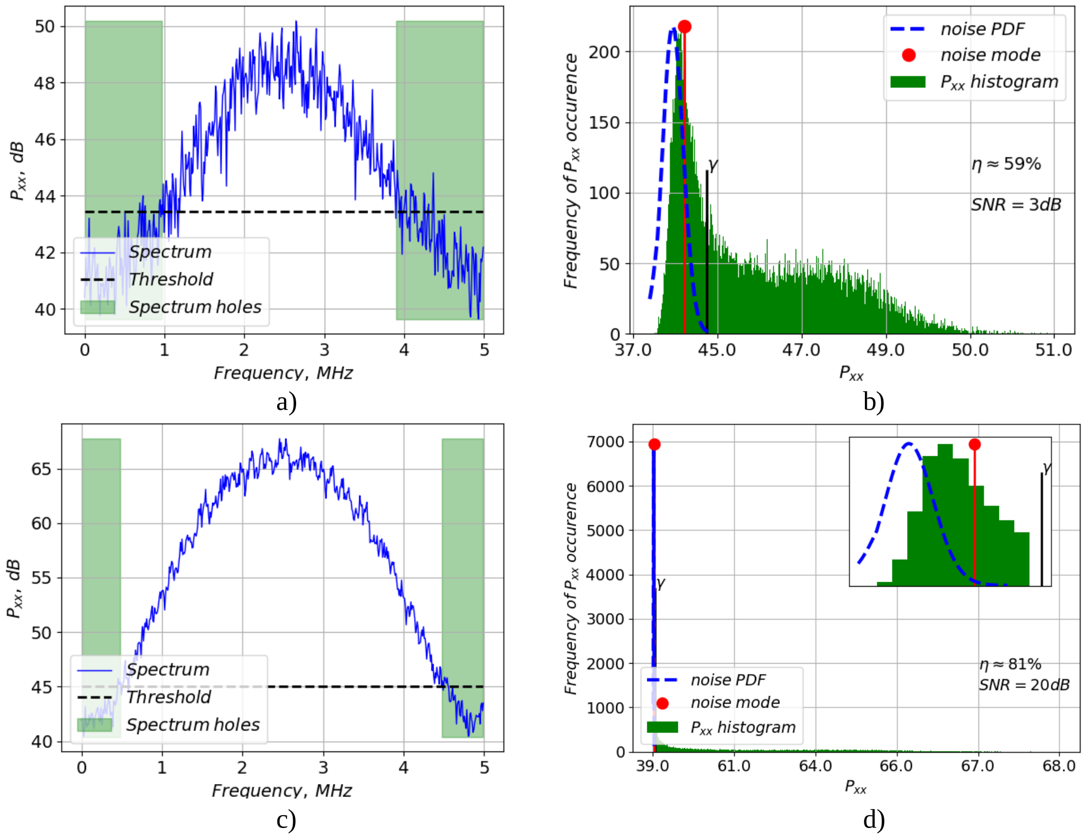

Fig. 5. Spectrum holes for RFS with PSK signal (a, c)
and corresponding histograms (b, d) for high spectrum occupancy

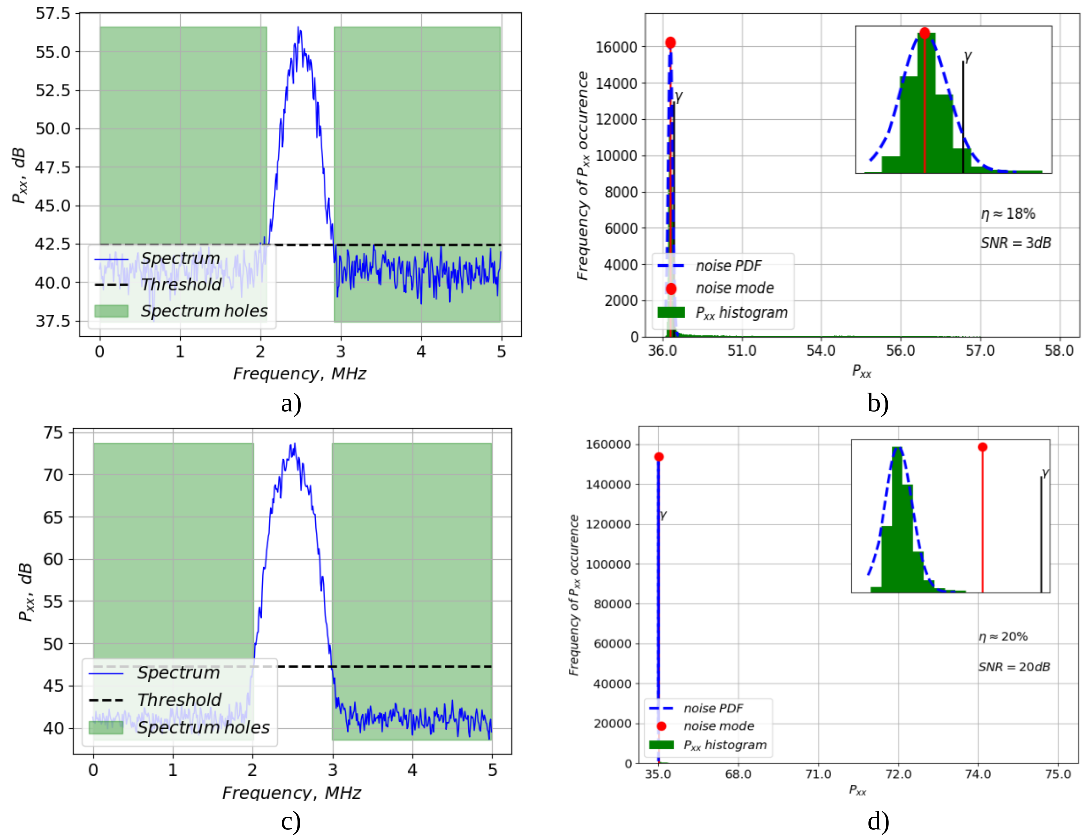

Fig. 6. Spectrum holes for RFS with PSK signal (a, c)
and corresponding histograms (b, d) for low spectrum occupancy

Despite the relatively large errors in estimates of noise mode value (see fig. 2), proposed method for both cases makes it possible to detect and determine frequency boundaries of spectrum holes.

Fig. 7 shows the dependence of detection probability of spectrum holes via SNR (calculated in time domain) for an OFDM signal at a band occupancy of about 85% and for a PSK signal with occupancy of about 80%. It is worth noting that for PSK signal, the occupancy level decreases as SNR decreases from 80% for SNR of 25 dB to 25% for SNR of -2 dB, which is due to the shape of the spectrum of this signal type and it was taken into account during the research. The determination of spectrum holes boundaries with an error of no more than 1 % of the spectrum width for OFDM signal and 10% for PSK signal was chosen as a criterion for spectrum holes detection.

As can be seen from fig. 7, developed method provides correct detection of spectrum holes with a probability of at least 0.9 for a probability of a false alarm of 0.1 at values of SNR of at least 5 dB and maximal occupancy of analyzed frequency band no more than 85% for a spectrum with a rectangular envelope. For PSK signal and band occupancy of 80%, these values of detection can be achieved at SNR of at least 12 dB.

The available literature does not provide qualitative results of existing algorithms for spectrum holes detection in conditions of high occupancy of RFS. Therefore, the comparison of the obtained results with the existing ones will be incorrect.

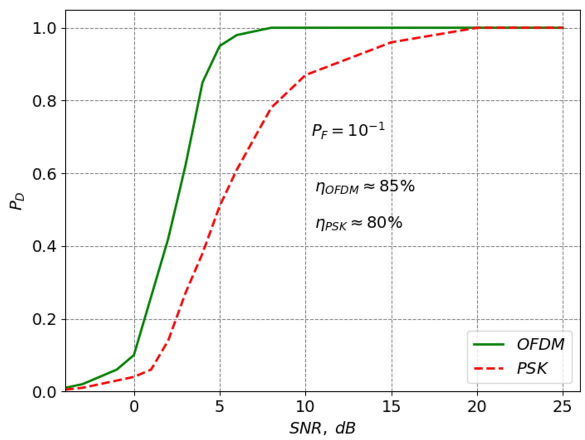

Fig. 7. Dependency of spectrum holes detection probability via SNR

Conclusion

The scientific novelty of proposed method is in development of an approach to spectrum holes detection of a given frequency band based on the use of histogram mode properties which corresponds to noise frequency samples. Method does not require knowledge of noise

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

power and shape of spectrum envelope, as well as the occupancy of analyzed frequency band.

Proposed method makes it possible to detect spectrum holes with a probability of at least 0.9 at values of SNR of at least 5 dB for the spectrum with a rectangular envelope and 12 dB for other forms of envelope under spectrum occupancy of up to 80 %.

Developed method requires the calculation of a histogram and the accumulation of a significant number of frequency samples in order to make a sufficiently accurate boundary between signal and noise samples. Therefore, in practical implementation of proposed method, it is recommended to calculate threshold value after some time intervals, since the noise level changes much more slowly than the signal level.

Future research directions

Prospects for further research in this direction are in improvement of methods for estimation noise mode at high values of SNR and low levels of spectrum occupancy, as well as in detection of several signals in analyzed frequency band.

Contribution of authors: development of research methodology – **Mykola Buhaiov**, statistic modeling – **Volodymyr Kliaznyka**, research of proposed method, editing – **Ihor Kozyura**, literature analysis, method research – **Denys Zavhorodnii**.

All the authors have read and agreed to the published version of the manuscript.

References (GOST 7.1.2006)

1. Spectrum Sensing for Cognitive Radio: Recent Advances and Future Challenge [Text] / A. Nasser et al. // Sensors. – 2021. – № 7. – P. 1-29. DOI: 10.3390/s21072408.

2. Leena, K. Enhanced Spectrum Sensing Techniques in Cognitive Radio Based Internet of Things [Text] / K. Leena, S. G. Hiremath // J. Phys.: Conf. Ser. 1921 012035. – 2021. – P. 1-13. DOI:10.1088/1742-6596/1921/1/ 012035.

3. Nallarasan, V. Spectrum Management Analysis for Cognitive Radio IoT [Text] / V. Nallarasan, K. Kottilingam // 2021 International Conference on Computer Communication and Informatics. ICCCI-2021, Jan. 27-29, 2021, Coimbatore, India. – 2021. – P. 1-5. DOI: 10.1109/ICCCI50826.2021.9402690.

4. Метод підвищення скритності систем передачі інформації на основі модуляції з ортогональним частотним розділенням і мультиплексуванням хаотичних піднесучих [Текст] / К. С. Васюта [та ін.] // Радіоелектронні і комп'ютерні системи. – 2021. – № 3(99). – С. 79-93. DOI: 10.32620/reks.2021.3.07.

5. Captain, K. M. Spectrum Sensing for Cognitive Radio. Fundamentals and Applications [Text] / K. M. Captain, M. V. Joshi. – NY. : CRC Press, 2022. – 256 p.

6. Elmasry, F. G. Dynamic Spectrum Access Decisions. Local, Distributed, Centralized, and Hybrid Designs [Text] / F. G. Elmasry. – NY. : John Wiley & Sons Ltd., 2021. – 728 p.

7. Liang, Y.-C. Dynamic Spectrum Management. From Cognitive Radio to Blockchain and Artificial Intelligence [Text] / Y.-C. Liang. – NY. : Springer, 2020. – 180 p.

8. Бугайов, М. В. Ітеративний метод виявлення радіосигналів на основі вирішуючих статистик [Текст] / М. В. Бугайов // Вісник НТУУ "КПІ". Серія Радіотехніка, Радіоапаратобудування. – 2020. – № 81. – С. 11-20. DOI: 10.20535/RADAP. 2020.18.11-20.

9. Безрук, В. М. Обнаружение незанятых частотных каналов в когнитивных радиосетях [Текст] / В. М. Безрук, С. А. Иваненко // Радиоэлектроника и информатика. – 2017. – №1(76). – С. 4–8.

10. Learning Based Spectrum Hole Detection for Cognitive Radio Communication [Text] / Z. Xu, I. Petrunin, A. Tsourdos, S. Ayub // 2019 IEEE/AIAA 38th Digital Avionics Systems Conference. DASC-2019, Sept. 8-12, 2019, San Diego, CA, USA – 2019. – P. 1-7. DOI: 10.1109/DASC43569.2019.9081799.

11. Sarala, B. Spectrum energy detection in cognitive radio networks based on a novel adaptive threshold energy detection method [Text] / B. Sarala, S. R. Devi, J. J. Sheela // Computer Communications. – 2020. – Vol. 152. – P. 1-7. DOI: 10.1016/j.comcom.2019. 12.058.

12. Eappen, G. Hybrid PSO-GSA for energy efficient spectrum sensing in cognitive radio network [Text] / G. Eappen, S. Thangavelu // Physical Communication. – 2020. – Vol. 40(1). – P. 1-9. DOI: 10.1016/j.phycom.2020.101091.

13. Mahendru, G. Novel Mathematical Model for Energy Detection Based Spectrum Sensing in Cognitive Radio Networks [Text] / G. Mahendru, A. Shukla, P. A. Banerjee // Wireless Pers Commun. – 2020. – Vol. 110. – P. 1237–1249. DOI: 10.1007/s11277-019-06783-3.

14. Spectrum Hole Detection for Cognitive Radio through Energy Detection using Random Forest [Text] / A. Mishra, V. Dehalwar, J. H. Jobanputra, M. L. Kolhe // 2020 International Conference for Emerging Technology. INCET-2020, June 5-7, 2020, Belgaum, India. – 2020. – P. 1-7. DOI: 10.1109/INCET49848.2020. 9154097.

15. Chaudhary, N. Identification of spectrum holes using energy detector based spectrum sensing [Text]/ N. Chaudhary, R. Mahajan // International Journal of Information Technology. – 2021. – Vol. 13, iss. 1. – P. 1243–1254. DOI: 10.1007/s41870-021-00662-6.

16. Sajeevua, S. A Novel Low Complexity High Resolution Spectrum Hole Detection Technique for Cogni-

tive Radio [Text] / S. Sajeevua, S. Vellaisamy // Electrical Engineering and Systems Science. – 2022. – P. 1-17. DOI: 10.48550/arXiv.2207.01098.

17. Bani, K. Hybrid Spectrum Sensing Using MD and ED for Cognitive Radio Networks [Text] / K. Bani, V. Kulkarni // J. Sens. Actuator Netw. – 2022. – Vol. 11(3). – P. 1-15. DOI: 10.3390/ jsan11030036.

18. Spectrum allocation for cognitive radio networks with non-deterministic bandwidth of spectrum hole [Text]/ J. Huang et al. // China Communications. – 2017. – Vol. 14, no. 3. – P. 87-96. DOI: 10.1109/CC.2017.7897325.

19. Кобзарь, А. И. Прикладная математическая статистика. Для инженеров и научных работников [Текст] / А. И. Кобзарь. – М. : ФИЗМАТЛИТ, 2006. – 816 с.

References (BSI)

1. Nasser, A. et al. Spectrum Sensing for Cognitive Radio: Recent Advances and Future Challenge. *Sensors*, 2021, no. 7, pp. 1-29. DOI: 10.3390/s21072408.

2. Leena, K., Hiremath, S. G. Enhanced Spectrum Sensing Techniques in Cognitive Radio Based Internet of Things. *J. Phys.: Conf. Ser*. 1921 012035, 2021, pp. 1-13. DOI: 10.1088/1742-6596/1921/1/ 012035.

3. Nallarasan, V., Kottilingam, K. Spectrum Management Analysis for Cognitive Radio IoT. *2021 International Conference on Computer Communication and Informatics. (ICCCI-2021).* Coimbatore, 2021, pp. 1-5. DOI: 10.1109/ICCCI50826. 2021.9402690.

4. Vasiuta, K. et al. Metod pidvyshchennya skrytnosti system peredachi informatsiyi na osnovi modulyatsiyi z ortohonal'nym chastotnym rozdilennyam i mul'typleksuvannyam khaotychnykh pidnesuchykh [The method of increasing the stealthiness of information transmission systems based on modulating with orthogonal frequency division and multiplexing of chaotic subcarriers]. *Radioelectronic and computer systems*, 2021, no. 3, pp. 79-93. DOI: 10.32620/reks.2021.3.07.

5. Captain, K. M., Joshi, M. V. *Spectrum Sensing for Cognitive Radio. Fundamentals and Applications*. NY., CRC Press, 2022. 256 p.

6. Elmasry, F. G. *Dynamic Spectrum Access Decisions. Local, Distributed, Centralized, and Hybrid Designs*. NY., John Wiley & Sons Ltd. Publ., 2021. 728 p.

7. Liang, Y.-C. *Dynamic Spectrum Management. From Cognitive Radio to Blockchain and Artificial Intelligence*. NY., Springer Publ., 2020. 180 p.

8. Buhaiov, M. V. *Iteratyvnyy metod vyyavlennya radiosyhnaliv na osnovi vyrishuyuchykh statystyk* [Iterative method for radiosignals detection based on decision statistics]. *Visnik NTUU KPI. Ser. Radioteh. radioaparatobuduv*, 2020, no. 81, pp. 11-20. DOI: 10.20535/RADAP.2020. 18.11-20.

9. Bezruk, V. M., Yvanenko, S. A. *Obnaruzhenye nezanyatukh chastotnukh kanalov v kohnytyvnukh radyosetyakh* [Detection of free frequency channels in cognitive radio networks]. *Radyoelektronyka y ynformatyka*, 2017, no. 1(76), pp. 4-8.

10. Xu, Z. *et al*. Learning Based Spectrum Hole Detection for Cognitive Radio Communication. *2019 IEEE/AIAA 38th Digital Avionics Systems Conference. (DASC-2019),* San Diego, CA, 2019, pp. 1-7. DOI: 10.1109/DASC43569.2019. 9081799.

11. Sarala, B., Devi, S. R., Sheela, J. J. Spectrum energy detection in cognitive radio networks based on a novel adaptive threshold energy detection method. *Computer Communications*, 2020, vol. 152, pp. 1-7. DOI: 10.1016/j.comcom.2019.12.058.

12. Eappen, G., Thangavelu, S. Hybrid PSO-GSA for energy efficient spectrum sensing in cognitive radio network. *Physical Communication*, 2020, vol. 40(1), pp. 1-9. DOI: 10.1016/j.phycom.2020.101091.

13. Mahendru, G., Shukla, A., Banerjee, P. A. Novel Mathematical Model for Energy Detection Based Spectrum Sensing in Cognitive Radio Networks. *Wireless Pers Commun*, 2020, vol. 110, pp. 1237–1249. DOI: 10.1007/s11277-019-06783-3.

14. Mishra, A. *et al*. Spectrum Hole Detection for Cognitive Radio through Energy Detection using Random Forest. *2020 International Conference for Emerging Technology. (INCET-2020),* Belgaum, 2020, pp. 1-7. DOI: 10.1109/INCET 49848.2020.9154097.

15. Chaudhary, N., Mahajan, R. Identification of spectrum holes using energy detector based spectrum sensing. *International Journal of Information Technology*, 2021, no. 13(1), pp. 1243–1254. DOI: 10.1007/s41870-021-00662-6.

16. Sajeevua, S., Vellaisamy, S.. A Novel Low Complexity High Resolution Spectrum Hole Detection Technique for Cognitive Radio. *Electrical Engineering and Systems Science*, 2022, pp. 1-17. DOI: 10.48550/arXiv.2207.01098.

17. Bani, K., Kulkarni, V. Hybrid Spectrum Sensing Using MD and ED for Cognitive Radio Networks. *J. Sens. Actuator Netw.*, 2022, vol. 11(3), pp. 1-15. DOI: 10.3390/ jsan11030036.

18. Huang, J. et al. Spectrum allocation for cognitive radio networks with non-deterministic bandwidth of spectrum hole. *China Communications*, 2017, vol. 14, iss. 3, pp. 87-96. DOI: 10.1109/CC.2017.7897325.

19. Kobzar, A. Y. *Prykladnaya matematycheskaya statystyka. Dlya ynzhenerov y nauchnukh rabotnykov* [Applied mathematical statistics. For engineers and scientists]. Moscow, FYZMATLYT Publ., 2006. 816 p.

Надійшла до редакції 12.09.2022, розглянута на редколегії 20.11.2022

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

МЕТОД ВИЯВЛЕННЯ ВІЛЬНИХ ЧАСТОТНИХ КАНАЛІВ НА ОСНОВІ АНАЛІЗУ МОД ГІСТОГРАМИ СПЕКТРАЛЬНИХ ВІДЛІКІВ

Микола Бугайов, Володимир Клязника,
Ігор Козюра, Денис Завгородній

Предметом вивчення в статті є процес виявлення та оцінювання меж вільних частотних каналів в умовах високої завантаженості спектра при використанні приймачів із вузькими миттєвими смугами аналізу. **Метою** роботи є підвищення ймовірності правильного виявлення вільних частотних каналів в умовах високої завантаженості радіочастотного спектра та змінного рівня шуму шляхом розроблення методу розділення сигнальних та шумових відліків на основі аналізу мод гістограми спектральних віддліків. **Завдання**: розроблення методу розділення сигнальних та шумових відліків у частотній області; розроблення методики пошуку мінімальної моди розподілу щільності ймовірностей; визначення частотних меж вільних ділянок радіочастотного спектра; формулювання рекомендацій щодо практичної реалізації розробленого методу. Використовуваними **методами** є: методи теорії ймовірностей та математичної статистики, методи статистичного моделювання. **Сутність** запропонованого методу полягає в розділенні множини частотних відліків енергетичного спектра із використанням порогу, отриманого для значення моди гістограми для шуму, та визначенні частотних меж вільних частотних каналів. Отримано такі **результати**. Виведено вираз для розрахунку значення порогу для розділення сигнальних і шумових відліків у частотній області із використанням значення шумової моди розподілу частотних відліків. Встановлено, що шумова мода має найменше значення серед решти мод, оскільки шумові відліки мають менші значення порівняно з сигнальними. Розроблено методику оцінювання значення шумової моди, що полягає в обчисленні гістограми значень частотних відліків енергетичного спектра та знаходженні того інтервалу розбиття, що відповідає значенню мінімальної моди. Запропоновано підхід до визначення частотних меж шумових ділянок спектра за наявності у смузі аналізу одного сигналу. **Висновки**. Розроблений метод дозволяє виявляти вільні частотні канали з ймовірністю не менше 0,9 при значеннях відношення сигнал-шум не менше 5 дБ для спектра з прямокутною обвідною та 12 дБ для інших обвідних в умовах завантаженості до 80 %.

Ключові слова: гістограма; мода; зайнятість спектра; тестова статистика; вільний частотний канал; періодограма Уелча.

Бугайов Микола Вікторович – канд. техн. наук, старш. дослід., заст. нач. науково-дослідного відділу наукового центру, Житомирський військовий інститут ім. С. П. Корольова, Житомир, Україна.

Клязника Володимир Вікторович – заст. нач. каф. радіоелектронної розвідки, Житомирський військовий інститут ім. С. П. Корольова, Житомир, Україна.

Козюра Ігор Вікторович – доц. каф. радіоелектронної розвідки, Житомирський військовий інститут ім. С. П. Корольова, Житомир, Україна.

Завгородній Денис Сергійович – канд. пед. наук, доц. каф. Тактики (Військово-Морських Сил), Інститут Військово-Морських Сил Національного університету "Одеська морська академія", Одеса, Україна.

Mykola Buhaiov – Candidate of Engineering Sciences, Senior Researcher, Deputy Chief of Research Department of the Scientific Center, Zhytomyr Military Institute of S. P. Korolov, Zhytomyr, Ukraine,
e-mail: karunen@ukr.net, ORCID: 0000-0003-0899-9843, WoS: AAO-1894-2021.

Volodymyr Kliaznyka – Deputy Head of Electronic Intelligence Department, Zhytomyr Military Institute of S. P. Korolov, Zhytomyr, Ukraine,
e-mail: vladvikt1982@gmail.com, ORCID: 0000-0003-3557-2052.

Ihor Kozyura – Associate Professor of Electronic Intelligence Department, Zhytomyr Military Institute of S. P. Korolov, Zhytomyr, Ukraine,
e-mail: ivk1102@i.ua, ORCID: 0000-0001-9711-7237.

Denys Zavhorodnii – Candidate of Pedagogical Sciences, associate professor of Tactics (Navy) Department, Navy Institute National University «Odessa Maritime Academy», Odessa, Ukraine,
e-mail: shturmam@gmail.com, ORCID: 0000-0003-3244-9163.