УДК 621.396

Spectrum Smoothing Method for OFDM Signals Detection in Frequency Selective Channel

Buhaiov M. V.

S. P. Korolov Military institute, Zhytomyr, Ukraine

E-mail: *karunen@ukr.net*

Orthogonal Frequency Division Multiplexing (OFDM) technology has become widespread in civil and military radio systems, especially in channels with frequency selective fading. Due to the large number of OFDM signal schemes, an urgent task for modern radio monitoring systems is development of methods and algorithms for detecting such signals that will be stable in the uncertainty of OFDM signal structure and electromagnetic environment. At the stage of detection, the characteristic feature of OFDM signal is presence of frequency channels in its spectrum envelope. In this research, an algorithm for detecting an OFDM signal in the frequency domain and for estimating the number of frequency channels and duration of the interval of orthogonality was developed. To make a decision whether signal is present in realization of the normalized to the energy spectrum, its variation was used. This approach avoids estimating noise power. In case of signal samples detecting spectrum is double-smoothed using moving average. This provides better smoothing than with a single long window. Thereafter, double thresholding is performed. The second threshold is calculated using samples that have not exceeded the first threshold. Samples that have exceeded the second threshold are considered signal. Next, a search is made for occupied frequencies with a given bandwidth. The samples located in this band are re-smoothed and give spectrum trend, which is used as a threshold to determine the boundaries of frequency channels. OFDM signal is considered detected if equidistant frequency channels were found. After that, duration of the interval of orthogonality is calculated. The proposed method requires a slight complication of the spectral analysis procedure based on the fast Fourier transform. Proposed method can be used for improving broadband radio monitoring systems and provide practically simultaneously implementation procedure of OFDM signal detection-recognition.

Key words: OFDM; smoothed spectrum; double thresholding; interval of orthogonality; frequency channel; frequency selective fading

DOI: 10.20535/RADAP.2021.85.33-40

Introduction

Nowadays using Orthogonal Frequency Division Multiplexing (OFDM) technology has become widespread in civil and military radio systems, especially in multipath channels, as it solves the problem of frequency selective fading and interference. This technology effectively uses frequency band and maintains a high speed information transfer [1]. OFDM is most often used in digital television (DVB) and digital radio (DAB), wireless communication standards LTE, WiMAX, Wi-Fi, WLAN, radar, software-defined radio, video transmission from unmanned aerial vehicles. Therefore, one of the main trends of modern radio monitoring is OFDM signal detection and its parameters estimation at low signal-to-noise ratio (SNR) and in frequency selective environment. Taking into account the variety of OFDM schemes, the urgent task is developing methods and algorithms for detecting such signals that will be stable in uncertainty of OFDM signal structure and electromagnetic environment.

1 Review of related works

The complexity of OFDM signal structure requires applying of non-standard approaches in solving radio monitoring problems. Therefore, in the scientific works of recent years, research of methods and algorithms for OFDM signals detecting and its parameters estimation are given considerable attention.

The largest group of detection methods is based on cyclostationary analysis [2–10]. These methods use peaks of cyclic autocorrelation function (ACF) as important features of OFDM signal, which are associated with the presence of guard interval and pilot tones. Sum of the cyclic ACF peaks, its maximum value or the ratio of the number of peaks with the same distance between them to the total number of peaks are most often chosen as test statistics. Threshold is defined as average value of the cyclic ACF for noise.

For these methods, increasing integration time provides increasing probability of detection by reducing noise variance. With decreasing duration of guard interval of OFDM signal detection characteristics deteriorate. Time window duration for analysis must be at least the duration of the OFDM symbol. Correlation detector works better than the energy one in channels with fading. In [11] to detect OFDM signals without a cyclic prefix, it is proposed to use energy ACF, which is insensitive to phase and frequency shifts.

In [12] it was proposed to perform a test for normality over the received signal and in case of a positive result perform a test for cyclostationarity. If process is cyclostationary, it is considered to be an OFDM signal and then number of subcarriers, symbol duration and cyclic prefix are estimated.

In [13] statistics derived from the second-order cyclic cumulant ratio for the time and frequency-time domains are used to recognize OFDM from a single-carrier signal. To solve this problem, it is proposed in [14] to analyze the pseudo-inverse spectrum. Test statistic in this case is ratio of periodic peaks sum to the sum of average values between these peaks.

There are also hybrid OFDM detection schemes, which consist of energy and cyclostationary detectors [15]. With a known value of the noise variance energy detector provides a higher detecting probability of OFDM than cyclostationary, and if it is inaccurate, it is advisable to use the latter.

To detect OFDM signals in time domain, a method that uses asymmetry and excess was proposed in [16]. A priori signal info is not required, but noise power is used to form threshold. Average value of excess absolute values for several OFDM symbols is chosen as test statistic.

In [17] it was proposed to use cepstrum estimates for characteristic features, which have 1-2 peaks for OFDM signal. Difference between maximum value of cepstrum and maximum value of its sidelobe was used as test statistic. Number of OFDM channels can be estimated by abscissa value of the cepstrum central peak.

In most of the considered methods, detection of OFDM signal is performed at the background of white noise, and value of threshold depends on the unknown value of its variance. However, in practice, narrowband signals fall into the analyzed frequency band and channel frequency characteristic changes in time. Also proposed methods often require implementation of complex signal transforms, but in the vast majority of software and hardware for radio monitoring as a basic signal transform fast Fourier transform (FFT) is usually used. Therefore improvement of methods for automatic detection and estimation of multifrequency multiphase signals parameters for modern radio monitoring systems based on spectrum analysis in a complex electromagnetic environment is an urgent task.

2 Purpose and objectives of research

The aim of this paper is to provide the ability to automatically detect and estimate OFDM signal main parameters in a complex electromagnetic environment.

3 Model of received OFDM signal

OFDM technology is a modulation scheme that uses a large number of closely spaced orthogonal carriers. Each carrier is modulated according to the usual modulation scheme at a low symbol rate maintaining total data rate, as in conventional schemes on one carrier in the same bandwidth. Low symbol rate allows us to use a guard interval and work with time delays and eliminate inter-symbol interference between carriers, as well as provides time and frequency synchronization. Amplitude and initial phase of each modulated tone depends on information bits it carries.

Data transmission based on OFDM technology is performed using frames. Each frame consists of a preamble and a number of OFDM data symbols. Before the start of the OFDM frame zero symbols (without power transmission) can be transmitted to estimate noise, interference levels and coarse timing [1]. Preamble consists of several parts and is designed to detect start of the frame, automatic gain control, time synchronization, shift of carrier frequency and channel characteristic estimation. Preamble also carries values of coding rate, packet length and type of modulation.

Pilot tones with a known structure are used to capture phase and equalize channel frequency characteristic. To eliminate Doppler effect, several carriers may not be modulated, and adjacent carriers leave zeros for easier selection of pilots. Continuous pilotes are transmitted at constant frequencies in each OFDM symbol, and distributed - uniformly over time and frequency.

Some signals use virtual carrier (carrier pass in the center of the spectrum). Power of pilot tones is usually higher than that of information carriers. Schematic structure of OFDM signal in time-frequency plane is shown in Fig. 1.

Data carriers can be grouped into logical channels. Each channel can have different modulation, power and encoding. Also, depending on signal propagation environment it is possible to use different modulation schemes for different carriers.

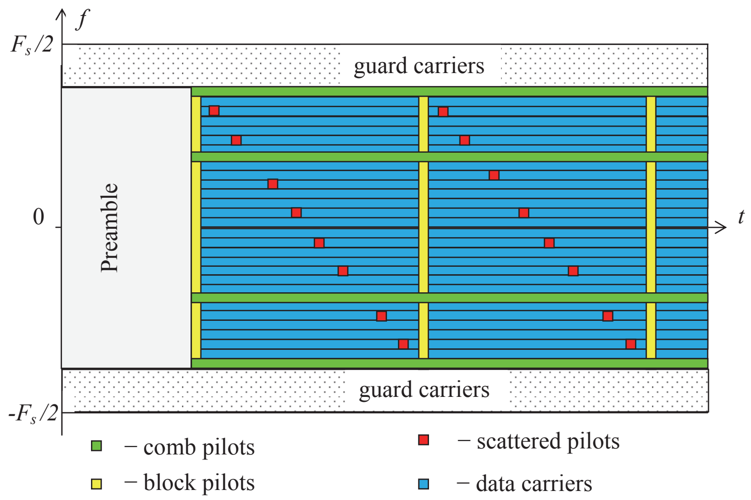


Fig. 1. OFDM signal structure in time-frequency domain

Important parameters of OFDM signal that can be used for its detection include:

duration of interval of orthogonality (integration) $T_d = N/f_s$, where N – FFT length, f_s – symbol rate;

duration of guard interval T_g;

OFDM symbol duration $T_s = T_d + T_g$;

number of information N_d, pilot N_{pc} and guard (virtual) tones N_{gc};

FFT length $N = N_d + N_{pc} + N_{gc}$;

carriers spacing – $\Delta f = 1/T_d$.

Unknown characteristics of OFDM signal that complicate its detection are structure of frames and preamble, scheme and structure of pilot tones.

Model of sample of OFDM symbol s_n in time domain can be represented as follows [1]:

$$s_n = \begin{cases} \frac{1}{N}\sum_{k=0}^{N-1} d_k e^{j2\pi\frac{kn}{N}}, & k = 0, 1, \ldots, N-1 \\ s(N+k), & k = -N_g, \ldots, -1 \end{cases}, \quad (1)$$

where $d_k = a_k + jb_k$ – complex data symbol; N_g – length of guard interval in samples.

According to the signal generation rule, it is obvious that in time domain its value at each moment will be a random variable with an approximately normal distribution.

For each communication standard structure of preamble and frames can differ significantly. Therefore, for detection of unknown OFDM signal, only specific and stable for that communication technology features should be used. In [18] it was shown that as such a feature of OFDM signal at the stage of detection can be considered its ripple spectrum shape due to frequency channels.

Let's assume following electronic environment for our research:

- analyzed signal mixture contains an unknown number of narrowband and OFDM signals;

- noise power is unknown, but in the analyzed frequency band it practically unchanged;

- bandwidth OFDM signal in analyzed frequency band is much larger than the spectrum width of other signals and their spectra do not overlap;

- a priori information about carrier frequencies and modulation parameters of all components of the received mixture are unknown.

Further received signal $x(t)$ will be considered as follows:

$$x(t) = s(t) * h(t) + \sum_{j=1}^{J} s_j(f_j, \Delta f_j, t) + \xi(t), \quad (2)$$

where $s(t)$ – OFDM signal;

$h(t)$ – channel impulse response;

$f_j, \Delta f_j$ – carrier frequency and bandwidth of j-th narrowband signal;

$\xi(t)$ – white zero-mean Gaussian noise.

Channel impulse response can be described by the following expression:

$$h = \sum_{i=1}^{N_r} (a_i + jb_i), \quad (3)$$

where N_r – uniformly distributed in range [3, 9] random value that corresponds to the number of signal propagation paths; a, b – coefficients with a standard normal distribution.

4 Methodology of OFDM detection based on smoothed spectrum analysis

According with the recommendations described in [19] for the detection and external parameters of OFDM signal estimation, it is advisable to use methods based on the calculation of power spectral density (PSD) and spectrum shape estimation.

A characteristic feature of OFDM signal is presence of frequency channels in the envelope of its spectrum. With a relatively long duration of the guard interval, there will be clearly visible frequency carriers in signal spectrum and it is possible to estimate their number, spacing between them and calculate the duration of interval of orthogonality. In [20] it was shown that at large integration intervals and high resolution of FFT (preferably 0,1Δf), the number of frequency channels can be determined by spectral estimates.

In fig. 2 an algorithm for OFDM signal detection in frequency domain based on presence of equidistant frequency channels is shown. In block 1 are entered values of FFT length N_{FFT}, number of averaging FFT realizations R, vector of moving average window lengths $\mathbf{w} = \{\mathrm{w}_1, \mathrm{w}_2, \mathrm{w}_3\}$, ΔF_{max} – maximum value of frequency spacing between individual frequency components, at which they are considered one signal, threshold values of the spectrum width ΔF_{tr} and the decisive statistics Q_{tr}, samples of received signal $x[n]$.

In block 2 sum of squares of R FFT modules is calculated. To avoid estimation the unknown noise power, in block 3 normalization of the vector of frequency samples to energy is implemented.

To decide whether the signal samples are present in calculated PSD we use some test statistic. In [21] it was shown that variation is the most effective one. Value of variation Q for vector Z is calculated in block 4. When calculated value of Q exceeds a certain threshold value Q_{tr} (block 5) processing of the PSD vector continues. Otherwise, next fragment of received signal is under processing. Since OFDM signal during such processing usually takes a large number of adjacent frequency samples value of Q_{tr} should be chosen at the level of $1{,}05/N_{FFT}$. In block 6 PSD is smoothed by double application of moving average using windows w_1 and w_2 with a length of about $0{,}002N_{FFT}$ each. This approach provides better smoothing than with a single long window. In block 7 an energy normalization operation, similar to the normalization considered in block 3, is performed.

To separate signal and noise samples, double thresholding of vector Y is performed. In the case of processing a complex signal, the first threshold is calculated by the following expression:

$$T_1 = \frac{1}{N_{FFT}} \left(1 + \frac{6}{\sqrt{R\mathrm{w}_1}}\right). \qquad (4)$$

If there are several signals in analyzed frequency band with different power levels, some weak signals may not exceed this threshold and will be missed. Therefore, the second threshold is calculated:

$$T_2 = \frac{\sum\limits_{N_n} Z_n}{N_n} \left(1 + \frac{6}{\sqrt{R\mathrm{w}_1}}\right), \qquad (5)$$

where Z_n – samples below T_1 threshold, N_n – their number.

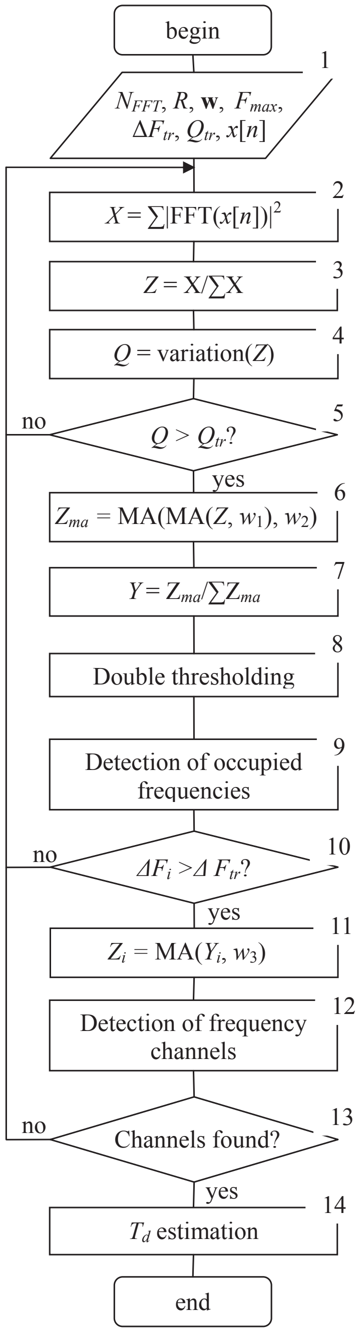


Fig. 2. Scheme of OFDM signal detection in frequency domain (MA – moving average)

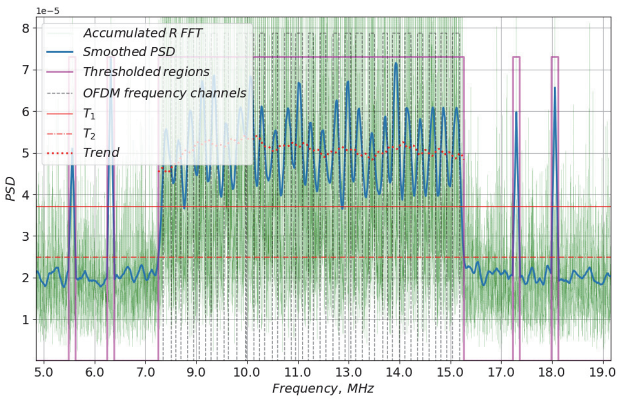
Frequency samples that exceed threshold T_2 are considered as signal and in block 9 procedure of calculating frequency limits of occupied frequencies is implemented. If spacing between some adjacent regions of the spectrum is less than ΔF_{max}, then these regions are combined. In those frequency bands whose width ΔF_i exceeds threshold value ΔF_{tr}, frequency channels of OFDM signal are searched. For this purpose, in block 11 selected frequency samples are smoothed using moving average with a window length $\mathrm{w}_3 \approx 0,02N_{FFT}$. This makes it possible to find signal spectrum trend

(Fig. 3) and use it as threshold to determine boundaries of frequency channels in frequency-selective channel. OFDM signal is considered to be detected if equidistant frequency channels are found in frequency band ΔF_i: variation of measured values of the central frequencies of channels do not exceed 0,5. In the case of deciding to detect OFDM signal in block 14 value of the interval of orthogonality T_d is calculated as:

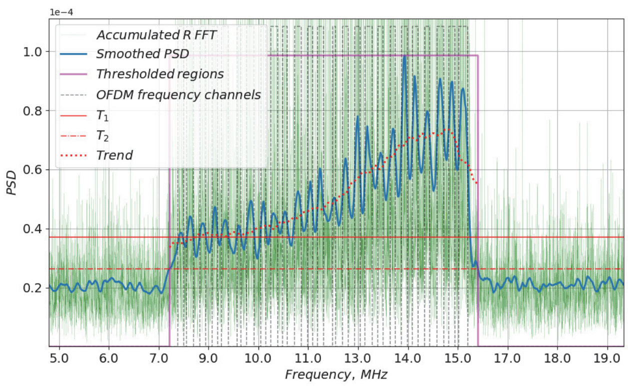
$$T_d = \frac{N_{FFT}}{F_s \Delta f}, \tag{6}$$

where F_s – sampling rate; Δf –carriers spacing.

Fig. 3 shows visualization of OFDM signal processing results for different types of channels in accordance with the steps proposed in Fig. 2 algorithm at N_{FFT}=2^{16}, $R = 6$ and $F_s = 50$ MHz. SNR for both cases was -6 dB. To the right and left of the spectrum of OFDM signal are narrowband signals. Duration of the guard interval was a quarter of the duration of OFDM symbol and number of frequency channels was 25. Analyzing obtained results we can assume that FFT length during signal generation is 32. Measured carriers spacing is about 312 kHz, which means that the interval of orthogonality is about 3,2 μs and duration of the information symbol is 0,1 μs.



(a)



(b)

Fig. 3. Visualization of OFDM processing in fading free channel (a) and in frequency-selective channel (b)

Shown in Fig. 3a spectrum corresponds to the case of a fading free channel or a channel that is stationary for one OFDM symbol. For large FFT lengths (tens of thousands), non-uniformity of the frequency characteristic of the time-varying channel is averaged using several FFT realizations. Fig. 3b corresponds to the case of a frequency-selective channel that is stationary within at least one FFT window.

Small values of averaged spectra R improves accuracy of determining OFDM signal start but deteriorate accuracy of determining boundaries of frequency channels, especially at low SNR and reduce information rate updating in the analyzed band. However R is mostly determined not by SNR but by the need to accumulate a sufficient number of frequency samples to detect frequency channels. In order for sufficiently appearing of frequency channels, length of the sequence of time samples to be analyzed must contain hundreds or thousands of OFDM symbols.

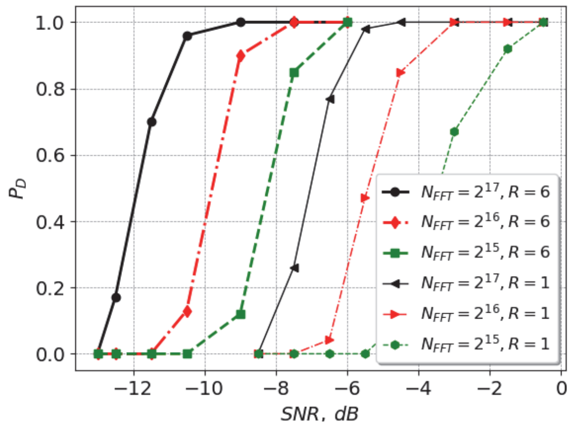
If in result of the algorithm (Fig. 2) implementation frequency channels are not detected, it is advisable to perform correlation analysis in a given frequency bandwidth ΔF_i. This approach will increase SNR and reject narrowband signals that fall into the band of the receiver. Correlation processing can also be performed after block 10 in parallel with the search for frequency channels. In addition, obtained value of the duration of the interval of orthogonality can greatly simplify correlation processing.

5 Simulation results

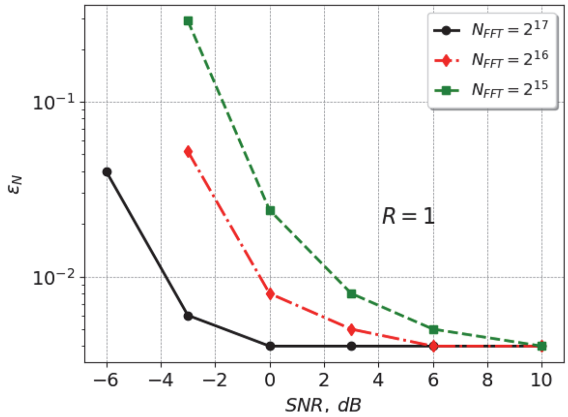
Efficiency of the developed method was checked by the method of statistical modeling. OFDM signal parameters were selected as follows: number of frequency channels (including 5 pilot tones) – 25, information symbol duration – $\tau_s = 0{,}1$ μs, data modulation – Quadrature Amplitude Modulation, sampling rate – $F_s = 50$ MHz. Length of the guard interval during experiment varied from 1/4 to 1/32 of the length of OFDM symbol. Positions of pilots: equidistant for one pilot carrier per OFDM symbol with a time offset of three symbols.

Effect of signal propagation was modeled by adding white Gaussian noise and frequency-selective fading. SNR value varied from -13 dB to 10 dB. Channel complex impulse response was modeled according to expression (3). When testing the algorithm for OFDM detection signal was considered detected if at least 80% of frequency channels are detected.

Fig. 4a shows detection curves of OFDM signal in fading channel for different FFT lengths and number of accumulated implementations R. Guard interval was a quarter of the length of the OFDM symbol. Relative error in estimating number of frequency channels ε_N as a function of SNR at $R = 1$ is shown in Fig. 4b. At high SNR ε_N does not depend on FFT length. For $R = 6$ ε_N decreases in 4-8 times.



(a)



(b)

Fig. 4. Detection curves for OFDM signal (a) and relative error of frequency channels estimated number via SNR (b)

In expression (6) there is no number of frequency channels. Therefore, at high values of ε_N (10-20 %) and even when the signal by a given criterion is not detected (at low values of SNR or deep fading), the error in estimating duration of the interval of orthogonality ε_T may be very small (less than 0,1 %). However, in most cases ε_T values are of the same order as ε_N.

When T_g is reduced by factor of 2 detection curves are shifted to the right by 3-4 dB and values of errors in estimating the parameters increase by about ten times. For $T_g < 1/16$ OFDM spectrum will be almost continuous which significantly limits the efficiency of spectral analysis for estimating frequency parameters. In such conditions detection of OFDM using the proposed method becomes impractical.

For a channel with frequency selective fading, which is stationary within OFDM symbol and non-stationary within FFT window detection curves will be shifted by 1-2 dB to the right. Relative error in estimating number of frequency channels as function of SNR is shown in Fig. 5. As we can see, for the case of frequency selective channel value of ε_N at high SNR will be smaller for larger FFT length. Error in estimating duration of the interval of orthogonality is approximately the same as ε_N.

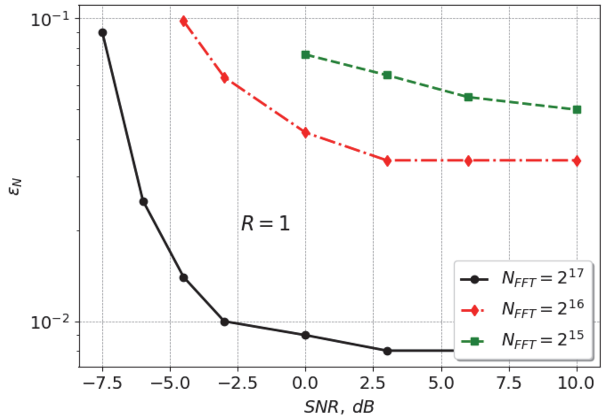


Fig. 5. Relative error of frequency channels number estimate via SNR

Since proposed algorithm combines several independent criteria it is difficult to say what will be the probability of false alarm, but we can assume that this value will be close to zero.

The closest to the proposed in this paper method, which also uses as one of the characteristic features of the OFDM signal is comb shape of its spectrum, given in [17]. However, this method allows you to estimate only the number of frequency channels. Unfortunately authors did not specify at which SNR their method remains stable.

Conclusions

Scientific novelty of the proposed method is in the sequential double smoothing of power spectrum with subsequent double thresholding, estimation of occupied frequencies and search for the frequency channels of OFDM signal. Implementation of the proposed method provides detection of OFDM signal and estimation of the number of its frequency channels and interval of orthogonality in case of frequency-selective channel. Reliability of conclusions is confirmed by results of statistical modeling.

Proposed method requires slight complication of the spectral analysis procedure based on FFT and may be used to increase the efficiency of broadband radio monitoring systems, namely the almost simultaneous implementation detection-recognition of OFDM signal.

Prospects for further research in this area should focus on development and research of methods for detecting and recognizing OFDM signals in a complex electromagnetic environment based on correlation processing.

References

[1] Fazel K., Kaiser S. (2008). Multi-Carrier and Spread Spectrum Systems: From OFDM and MC-CDMA to LTE and WiMAX. 2nd Edition. *John Wiley & Sons, Ltd*, 380 p. DOI:10.1002/9780470714249.

[2] Castro M. E. (2011). Cyclostationary detection for OFDM in cognitive radio systems. Theses, Dissertations, and Student Research from Electrical & Computer Engineering. *University of Nebraska*, 113 p.

[3] Sohn S. H., Han N., Kim J. M. and Kim J. W. (2007). OFDM Signal Sensing Method Based on Cyclostationary Detection. *2007 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, pp. 63-68. doi: 10.1109/CROWNCOM.2007.4549773.

[4] Gonzáles G., Cousseau J., Gregorio F., Wichman R., Werner S. (2011). A study of OFDM signal detection using cyclostationarity. *ResearchGate*, pp. 1-6.

[5] Kim M., Po K., Takada J.-i. (2010). Performance Enhancement of Cyclostationarity Detector by Utilizing Multiple Cyclic Frequencies of OFDM Signals. *2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, pp. 1-8, doi: 10.1109/DYSPAN.2010.5457876.

[6] Bixio L., Oliveri G., Ottonello M., Regazzoni C. S. (2009). OFDM Recognition Based on Cyclostationary Analysis in an Open Spectrum Scenario. *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, pp. 1-5. DOI: 10.1109/VETECS.2009.5073718.

[7] Muzaffar M. U., El-Tarhuni M., Assaleh K. (2012). Learning-based Spectrum Sensing in OFDM Cognitive Radios. *COCORA 2012. The Second International Conference on Advances in Cognitive Radio*, pp. 57-62.

[8] Vizziello A., Akyildiz I. F., Agusti R., Favalli L., Savazzi P. (2010). OFDM Signal Type Recognition and Adaptability Effects in Cognitive Radio Networks. *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*, pp. 1-5. DOI: 10.1109/GLOCOM.2010.5683103.

[9] Lushanur R. M. (2014). Study of the cyclostationarity properties of various signals of opportunity. Master of Science Thesis. *Tampere university of technology*, 119 p.

[10] Noguet D., Biard L., Laugeois M. (2010). Cyclostationarity Detectors for Cognitive Radio: Architectural Tradeoffs. *EURASIP Journal on Wireless Communications and Networking*, Article number: 526429 (2010). doi:10.1155/2010/526429.

[11] Le Nir, V., van Waterschoot, T., Moonen, M. et al. (2009). Blind CP-OFDM and ZP-OFDM Parameter Estimation in Frequency Selective Channels. *EURASIP Journal on Wireless Communications and Networking*, Article number: 315765 (2009). doi:10.1155/2009/315765.

[12] Li H., Bar-Ness Y., Abdi A., Somekh O. S., Su W. (2006). OFDM Modulation Classification and Parameters Extraction. *2006 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, pp. 1-6, doi: 10.1109/CROWNCOM.2006.363474.

[13] Sun, Z., Chen, Y., Liu, S. et al. (2014). Cyclostationarity-based joint domain approach to blind recognition of SCLD and OFDM signals. *EURASIP Journal on Advances in Signal Processing*, Article number: 5 (2014). doi:10.1186/1687-6180-2014-5.

[14] Tang, W., Cha, H., Wei, M., Tian, B., Ren, X. (2018). Identification method for OFDM signal based on fractal box dimension and pseudo-inverse spectrum. *APSIPA Transactions on Signal and Information Processing*, Vol. 7, E16. doi:10.1017/ATSIP.2018.19.

[15] Karami E., Dobre O. A. (2018). Identification of SM-OFDM and AL-OFDM Signals Based on Their Second-Order Cyclostationarity. *Cornell University*, 36 p.

[16] Haque M., Sugiura Y., Shimamura T. (2019). Spectrum Sensing Based on Higher Order Statistics for OFDM Systems over Multipath Fading Channels in Cognitive Radio. *Journal of Signal Processing*, Vol. 23, Iss. 6, pp. 257-266. DOI:10.2299/jsp.23.257.

[17] Liedtke F., Albers U. (2008). Evaluation of features for the automatic recognition of OFDM signals in monitoring or cognitive receivers. *Journal of telecommunications and information technology*, pp. 30-36.

[18] Buhaiov M. V. Analysis of high frequency OFDM modems signals in interest of radiomonitoring. (2020). *Vceni zapiski Tavrijskogo nacionalnogo universitetu imeni V. I. Vernadskogo. Seria Tehnicni nauki*, Vol. 31 (70), Iss. 5, pp. 30–35. DOI: 10.32838/2663-5941/2020.5/06. [In Ukrainian].

[19] Recommendation ITU-R SM.1600-3. Technical identification of digital signals SM Series Spectrum management. (2017). *ITU*, 25 p.

[20] Handbook. Spectrum monitoring. (2011). *ITU*, 678 p.

[21] Buhaiov M. V. (2020). Iterative Method of Radiosignals Detection Based on Decision Statistics. *Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia*, Vol. 81, pp. 11–20. doi: 10.20535/RADAP.2020.81.11-20. [In Ukrainian].

Метод виявлення OFDM сигналів в умовах частотно-селективних завмирань на основі аналізу згладженого спектра

Бугайов М. В.

На даний час в радіосистемах цивільного та військового призначення широкого поширення набуло використання технології OFDM, особливо при роботі в каналах із частотно-селективними завмираннями. Через значну кількість схем побудови OFDM сигналів актуальним завданням для сучасних систем радіомоніторингу є розроблення методів та алгоритмів виявлення таких сигналів, які будуть стійкими щодо невизначеності структури OFDM сигналу та електромагнітної обстановки. На етапі виявлення характерною ознакою OFDM сигналу обрано наявність частотних каналів в згинаючій його спектра. Розроблено алгоритм виявлення OFDM сигналу в частотній області, а також оцінюванні кількості частотних каналів і тривалості інтервалу ортогональності. Для прийняття рішення про наявність сигнальних відліків у розрахованій реалізації нормованого до енергії спектра використано його варіацію. Такий підхід дозволяє уникнути оцінювання потужності шуму. У разі виявлення частотних відліків проводиться подвійне згладжування спектра за допомогою ковзаючого середнього. Це забезпечує краще згладжування ніж за допомогою одного вікна великої довжини. Після цього

проводиться подвійна порогова обробка. Другий поріг розраховується із використанням відліків, що не перевищили перший поріг. Відліки, що перевищили другий поріг вважаються сигнальними. Далі проводиться пошук зайнятих ділянок частот із заданою шириною смуги. Відліки, що знаходяться у цій смузі ще раз згладжуються, що дозволяє отримати тренд спектра, який використовується як поріг для визначення меж частотних каналів. OFDM сигнал вважається виявленим, якщо було знайдено еквідистантні частотні канали. Після цього розраховується тривалість інтервалу ортогональності. Запропонований метод потребує незначного ускладнення процедури спектрального аналізу на основі швидкого перетворення Фур'є. Метод може бути використаний для підвищення ефективності роботи широкосмугових систем радіомоніторингу, а саме практично одночасної реалізації функції виявлення-розпізнавання OFDM сигналу.

Ключові слова: OFDM; згладжений спектр; подвійна порогова обробка; інтервал ортогональності; частотний канал; частотно-селективні завмирання

Метод обнаружения OFDM сигналов в условиях частотно-селективных замираний на основе анализа сглаженного спектра

Бугайов Н. В.

В настоящее время в радиосистемах гражданского и военного назначения широкое распространение получило использование технологии OFDM, особенно при работе в каналах с частотно-селективными замираниями. Из-за большого количества схем построения OFDM сигналов актуальной задачей для современных систем радиомониторинга является разработка методов и алгоритмов обнаружения таких сигналов, устойчивых относительно неопределенности структуры OFDM сигнала и электромагнитной обстановки. На этапе обнаружения характерным признаком OFDM сигнала выбрано наличие частотных каналов в огибающей его спектра. Разработан алгоритм обнаружения OFDM сигнала в частотной области, а также оценки количества частотных каналов и длительности интервала ортогональности. Для принятия решения о наличии сигнальных отсчетов в рассчитанной реализации нормированного к энергии спектра использовано его вариацию. Такой подход позволяет избежать оценки мощности шума. В случае обнаружения частотных отсчетов проводится двойное сглаживание спектра с помощью скользящего среднего. Это обеспечивает лучшее сглаживание чем с помощью одного окна большой длины. После этого выполняется двойная пороговая обработка. Второй порог рассчитывается с использованием отсчетов, которые не превысили первый порог. Отсчеты, превысившие второй порог, считаются сигнальными. Далее производится поиск занятых участков частот с заданной шириной полосы. Отсчеты, находящиеся в этой полосе повторно сглаживаются, что позволяет получить тренд спектра, который используется как порог для определения границ частотных каналов. OFDM сигнал считается обнаруженным, если были найдены эквидистантные частотные каналы. После этого рассчитывается длительность интервала ортогональности. Предложенный метод требует незначительного усложнения процедуры спектрального анализа на основе быстрого преобразования Фурье. Метод может быть использован для повышения эффективности работы широкополосных систем радиомониторинга, а именно практически одновременной реализации функции обнаружения-распознавания OFDM сигнала.

Ключевые слова: OFDM; сглаженный спектр; двойная пороговая обработка; интервал ортогональности; частотный канал; частотно-селективные замирания