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METHOD OF SIGNALS FORMING FOR HIGH-SPEED RADIO ACCESS SYSTEMS 5G

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ABSTRACT

This article presents the results of the research of a new method of signal generation for advanced wireless access systems, including cognitive radio systems, which allows to increase the spectral efficiency of the system and data transfer speed as well. Communication systems built on the basis of the architecture of software-configurable radio with cognitive radio algorithms have good perspectives, especially in the age of 5G- systems development. However, the signals that are used in modern radio systems (the signals from the orthogonal frequency division multiplexing Ortogonal Frequency Division Multiplex (OFDM)) have a number of significant disadvantages, one of which is the high level of side lobes of certain subcarriers that does not allow to provide potential spectral efficiency of high-speed radio access systems. This article describes new method of signals formation which is based on application of the new baseline signal shaping functions, the main feature of which is the ability for adaptive change of the level of energy localization in frequency and time area of basis vector. The use of the given basis allows not only to generate signals with a low level of lateral lobes in a group signal spectrum, but also with the changing structure of the spectrum, which can adaptively adjust to the existing electromagnetic environment in the channel, thus formed, while the process of adaptation in empty areas of spectrum, there is low enough level of interference noise that cannot be achieved using signals with orthogonal frequency division multiplexing. The work states the results of the research conducted on the sustainability assessment to the effect of additive white Gaussian noise using computer modeling. Besides the assessment proposed in the article spectral efficiency was carried out.

Keywords: *Cognitive Radio Communication System, OFDM, Spectral Efficiency, Spectral Mask, Dynamic Spectrum, Subcarrier, Forming Function, Orthogonality, 5G.*

1. INTRODUCTION

The rapid development and introduction of high-speed radio access technology leads to the fact that fewer radio frequency resources remain for them. However, at the same time, requirements of subscribers for the increase of speed of information transfer, types and quality of service are growing, that taking into consideration a large number of different radio devices simultaneously working on some areas, lead to the problem of electromagnetic compatibility of radio sets, and as practice shows to the lack of effectiveness of the radio spectrum use. According to predictions, future dynamics of mobile market leads to exponential growth of video traffic, minimum time delays in the network, a high level of connection reliability, a large density of radio devices and an increase of data rate by more than 100 times. It can be reached by the use and construction of smart high density radio systems with more sophisticated modulation techniques, access to channel resources, cloud services and routing protocols. This is the class of systems of the next generation (5 G) that will be able to cope with the challenges of the mobile market and satisfy existing requirements. It is possible to distinguish the main technical requirements for 5G networks on the basis of conducted studies and surveys [1-3]:

- new radio interface with small cells should be based on new forms of oscillations, new types of duplex, simple and flexible protocol link layer, higher modulation orders, effective methods of compensation system interference and multidimensional antenna systems (Massive MIMO);

- new architecture of radio net– distribution of the recourses and their management in heterogeneous architecture HetNet , remodel radio and net SDR and SDN elements (Software Defined

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Radio, Software Defined Networks), passing of user's data and managing in different physical areas (Physical separation between data&control planes);

- radio frequency resource – the use of high frequency bands including the range of millimeter waves, a new licensing regime, the use of licensed and unlicensed spectrum, the joint use of spectrum (Spectrum sharing), the combined use of the spectrum of indoor and outdoor environment;

- intellectual and adaptive networks – stochastic and adaptive use of network resources, the detection of the available spectrum (Spectrum sensing) and its use on the principles of cognitive radio, self-managed and automated network. General requirements for 5G systems are shown in Figure 1.

It becomes evident that 5G networks should apply advanced information transfer technologies to ensure rational use of the allocated radio spectrum, the maximum spectral efficiency and high-speed access with support for many new telecommunication services [2,3].

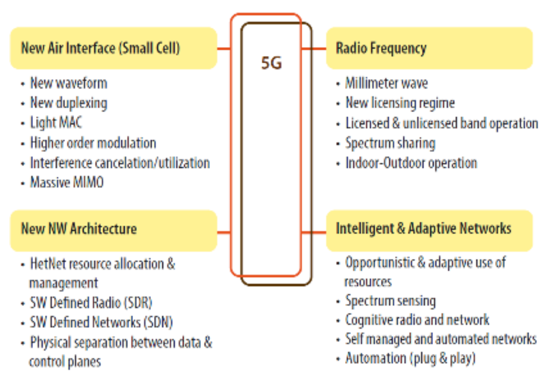

Figure 1. Requirements For 5G Networks

To date, it seems rational integrated use of more effective methods of multiple access, among which an play an important role is non-orthogonal methods of separation [5].

2. REVIEW OF PREVIOUS STUDIES AND PROBLEM STATEMENT

As it is known from scientific works [3-6] in modern radio assess systems, including cognitive radio system for information transmitting and receiving, the signals with orthogonal frequency multiplexing (Ortogonal Frequency Division Multiplex or OFDM) are used. This method was chosen for a number of reasons; one of them is the reduction of intra-system disturbances, resistance to a multipath effect in channel and the simplicity of a signal processing in user devices. However, it should be noted that one of the main disadvantages of OFDM signals is a general impossibility to achieve the maximum user data rates at simultaneous servicing of subscribers, and within the context of the requirements for the 5G network this aspect becomes particularly topical. In addition, the allocation of channel resources requires a strict synchronization which entails additional time delays in the radio interface, which are unacceptable in case of numerous connections in real time mode. However, it should be noted that one of the main disadvantages of OFDM signals is sufficiently slow decay of sidelobe energy enveloping OFDM signal subcarrier. This is the most significant disadvantage while using in systems where it is necessary to allocate users with different priority or, if necessary, to form empty areas in the signal to adapt to the complicated electromagnetic environment. These deficiencies sufficiently well covered in the literature and studied in detail [7-10]. In such cases it is impossible to reach high values of spectral and power efficiency, algorithms of synchronization become essentially complicated, meanwhile reducing the stability of work of information transfer system as a whole. Thus the use of OFDM signals in intelligent radio systems of high density is not an effective solution; therefore, various modifications of this type of signals that allow to achieve high values of the spectral and power efficiency are developed. The most well known signals are based on filter banks such as FBMC and developed on their basis, cosine-modulated multi-frequency SMT signals and multi-frequency signals with a shift of the quadrature SMT component [11]. It should be noted, however, that the mentioned signals have a number of disadvantages in the field of their application in 5G systems, among which are the following ones:

- relative complexity of forming blank areas in spectrum of the transmitted signal due to absence in such a case, of orthogonality between the basic functions and therefore degradation of noise immunity [11];

- absence of adaptability while signal forming due to a rigid binding to the frequency step ($\Delta f = 1/T$) that allows to change time-and-frequency properties of signal dynamically depending on conditions in the transfer channel and while base network loading [8].

- calculation complexity of formation process and FBMC signals processing on DSP board [11].

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These modifications of OFDM signal are fully described and investigated in [11], therefore, the comparative analysis form the point of view of noise immunity between the proposed new type of signal and OFDM signals is provided in the paper. The comparison of derivatives signals of OFDM, such as FBMC, CMT and SMT against each other in the article is not provided, in order not to go beyond the scope of this subject and, if necessary, these studies can be seen in detail if refer to [11]. However, the comparison of signal types mentioned above in terms of localization of the signal spectrum in the frequency domain is provided in the paper.

Thus the scientific paper of the authors is devoted to research and development of new and advanced methods of signal generation for advanced communication systems of the 5G generation and is of a great importance, since the solutions proposed in it allow to overcome to some extent the requirements set for 5G systems. The paper proposes a new approach to the formation of signals to transmit information with the maximum spectral efficiency and the ability to dynamical adaptation of the time-frequency parameters of the transmitted signal to the electromagnetic environment on the air. The analysis of the literature has shown that the required features and functions cannot be fully implemented when using traditional approaches such as OFDM signals, and its signal derivatives. Therefore, the ability to transfer information with the spectral efficiency, exceeding OFDM signals at a given noise immunity is one of the key scientific questions, this study is devoted to.

3. METHODOLOGY

3.1 Mathematical basis of the methodology

The paper proposes a method of signals forming with variable frequency characteristics for high-speed radio access systems. The proposed method is based on the use of subcarrier with a low level of out-of-band radiation, i.e., rapid decline of energy of sidelobe envelope subcarrier signal. One of the varieties of these signals are the following:

$$v_k(t) = A_k g(t)\cos(\omega_0 t + \omega_k t + \varphi_k), \quad (1)$$

where g(t) – represents the following envelope:

$$g(t) = \frac{\sin\left(\frac{2\pi}{a_1 T}t\right)}{\left(\frac{2\pi}{a_1 T}t\right)}, \quad (2)$$

where ω_0 – circular frequency carrier oscillations; $\varphi_k(t) = \Delta\omega kt + \varphi_k$, $\Delta\omega = 2\pi / T$, A_k – amplitude of k-th harmonic; $\omega_k = \Delta\omega k$ – a step between signal carriers, t – time, T – duration of a signal (2); a_1 – the factor adjusting duration of the basic petal of function (2); k=0,1,…N-1 – a serial number of harmonious fluctuation which is usually called as a subcarrier.

However, to ensure the full signal energy localization with envelope (2) at a given frequency area, their duration should match infinity i.e. $t \in (-\infty, \infty)$ that it is almost impossible to realize in computer engineering. So, the signals of such kind (1) are limited by special windowing function *r (t)* in time area.

$$r(t) = \begin{cases} \left(\frac{\sin\left(\frac{2\pi}{a_2 T}t\right)}{\left(\frac{2\pi}{a_2 T}t\right)}\right)^b, t \in [-a_2 T/2, a_2 T/2] \\ 0, t \notin [-a_2 T/2, a_2 T/2] \end{cases}; \quad (3)$$

a_2 – coefficient regulating the length of the envelope signal $v_k(t)$,

b – coefficient providing suppression of side pulses of function (2). Accordingly, signal of type (1) can be represented in the following way:

$$v_k(t) = A_k r(t) g(t)\cos(\omega_0 t + \omega_k t + \varphi_k), \quad (4)$$

Formative function *r(t)* allows to bring value of the signal (4) to zero, with the value $t = \pm a_2 T/2$, that will ensures reduction of differential amplitudes between separate signals while their serial transfer. Figure 2 shows the process of enveloping function $v_k(t)$ formation while using generate function *r(t)* and *g(t)*.

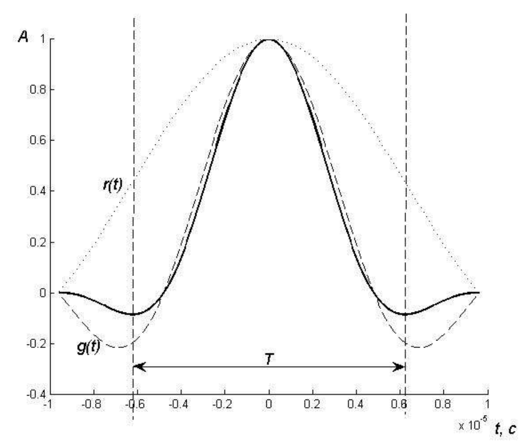

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Figure 2. Formation Of The Envelope Function $V_k(T)$

Formation of enveloping curve which is the basic function by means of functions *r(t)* and *g(t)* provides greater flexibility and adaptability of a signal being formed on its basis. Adjusting the parameters a_1, a_2, b make it is possible to vary the duration of the resultant signal; level of out of band emission of spectrum core functions and, consequently, the signal being transmitted, the width of the spectrum of a separate subcarrier. These features of the proposed approach provide opportunities for creation of adaptive and flexible transmission systems, where it is possible to provide maximum spectral efficiency of the transmitted signals, taking into account the negative factors of the communication channel that is impossible to do while using FBMC and OFDM signals.

Formula (1) can be expressed in the following way:

$$v_k(t) = \mathrm{Re}(X_k q_k(t))\cos(\omega_0 t) - \mathrm{Im}(X_k q_k(t))\sin(\omega_0 t) \quad (5)$$

where function $q_k(t)$ is complex and looks like:

$$q_k(t) = r(t)g(t)(\cos\omega_k t + i\sin\omega_k t), \quad (6)$$

X_k – modulation QAM symbols.

Final generated signal that is based on subcarriers (5) can be represented in the following way:

$$s_v(t) = \mathrm{Re}\left(\sum_{k=0}^{N-1} X_k q_k(t)\right)\cos(\omega_0 t) + \mathrm{Im}\left(\sum_{k=0}^{N-1} X_k q_k(t)\right)\sin(\omega_0 t), \quad (7)$$

It should be noted that the provision of an adequate level of noise stability in large ensemble of uncorrelated forms is possible while using orthogonal signal basis. Therefore, it is necessary to orthogonalize a set of base functions $s_v(t)$, for example, using Gram-Schmidt procedure [13].

Taking into consideration the fact that the proposed in the article method has the ability to adjust adaptively the frequency-time parameters of the transmitted signal for the electromagnetic environment on radio waves, providing maximum spectral efficiency, it absolutely meets the requirements for the use in advanced wireless such communication systems as 5G. Accordingly, systems built on its basis can have intellectual and adaptive functions [14-16], i.e., having the ability to adapt for the existing electromagnetic environment by detecting the available spectrum and use it on the principles of cognitive radio. These aspects allow dynamically to change the duration, the level of out-of-band radiation of the signal being transmitted to them, occupied the frequency range and number of used subcarriers according to the load and distribution of channel resources of base radionetwork. Thus taking into account the characteristics of radio communication channels, ensuring maximum efficiency and productivity of wireless communication systems in general [16].

3.2 Adaptation of the methodology for implementation of microprocessor technology elements

In a signal of such type (7) it is technically possible to adapt for the existing electromagnetic environment with the help of preformed spectral channel mask obtained on the basis of its sensing [17-19]. Thus, according to the received spectral mask frequency intervals (subcarrier numbers) $v_k(t)$) are defined, they should have zero energy while transmitting the resulting signal to the channel and after orthogonalization process resulting generated signal, it is necessary to present in the following way:

$$s_v^o(t) = \mathrm{Re}\left(\sum_{k=0}^{n_1} X_k q_k^o(t) + \sum_{k=n_2}^{N-1} X_k q_k^o(t)\right)\cos(\omega_0 t) + \mathrm{Im}\left(\sum_{k=0}^{n_1} X_k q_k^o(t) + \sum_{k=n_2}^{N-1} X_k q_k^o(t)\right)\sin(\omega_0 t), \quad (8)$$

where *n1* and *n2* – borders of a range of serial numbers of not used orthogonal functions, providing blank interval of the spectrum of the resulting signal.

To realize signal (8) on computer devices it is necessary operate with discrete values, a set of functions (4) is appropriate to represent in the form of Q, each element of which will be discrete count:

$$q_{k,l} = q_k(\Delta t(l - L - 1)), \quad (9)$$

where Δt – the period of digitization, $l=1,2,\ldots,2L$, , L – the whole part of the attitude $aT/(2\Delta t)$. So the formula (9) can be presented in a discrete type in the following way:

$$q_{k,l} = \left(\frac{\sin\left(\frac{\pi(l-L-1)}{L}\right)}{\left(\frac{\pi(l-L-1)}{L}\right)}\right)^b \left(\frac{\sin\left(\frac{a\pi(l-L-1)}{L}\right)}{\left(\frac{a\pi(l-L-1)}{L}\right)}\right)\left(\cos\frac{a\pi k(l-L-1)}{L} + i\sin\frac{a\pi k(l-L-1)}{L}\right) \quad (10)$$

The next step is the procedure of Gram-Schmidt orthogonalizaiton for the rows of the matrix *Q*.

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Thus, the procedure of forming a discrete integrated envelope will look like :

$$S = X \cdot Q^{o}, \quad (11)$$

Where Q^0 – matrix after orthogonalization of matrix Q; X is vector of complex symbols of the m-like modulation systems (QPSK, QAM-16, etc.). Complex symbols are formed from the set of information bits to be transmitted. Operations (9-11) can be simply done on a digital signal processor or programmed logic integrated circuit.

The final stage of signal (8) formation is digital-analog conversion of quadrature and in-phase components of complex vector $\vec{S}$ into analog form and its further processing in the quadrature modulator, which is implemented in the high-path transmitter.

4. THE EXPERIMENTAL RESEARCH OF NOISE STABILITY AND SPECTRAL EFFICIENCY

4.1 Noise immunity without additional subcarriers

Considered in the paper signals of the form (8) have been studied in detail in [20] from point of view of spectral efficiency and the rate of decline energy of the spectrum during the formation of empty regions in the spectrum, so the main emphasis in this work is done on the study of noise immunity. While studying noise stability of the method proposed in the article additive Gaussian noise with zero mathematical expectation generated in MatLab was used. A characteristic feature of this type of interference is that it is independent from the signal and occurs even when the input signal of the receiver is missing. The noise signal used in the experiment is characterized by the following probability density:

$$\omega(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-m)^2}{2\sigma^2}\right]; \quad (12)$$

Where $\omega(x)$ – the probability density of a random value;

σ^2 – dispersion of a random value;

m – mathematical expectation of the random value.

The simulation results are shown in Figure 3. In the experiment following parameters were used: OFDM signals from the occupied bandwidth of 20 MHz, duration – 12.8 microseconds and 202 subcarriers, in the process of modeling the transmission of OFDM signals was carried out sequentially. While evaluating the noise immunity of the signals (8) there were following parameters: bandwidth – 20 MHz, the length – 06.25 ms, the number of subcarriers – 256, for modulation of subcarriers – QAM-16. In the process of modeling the transmission of signals was carried out with severe inter-symbol interference with advance of 11.2 microseconds.

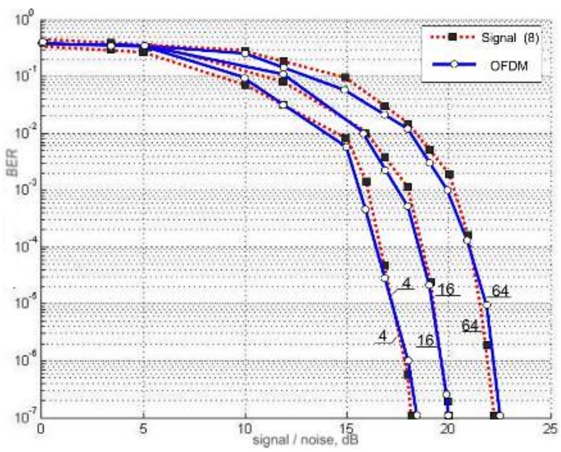

Figure 3. Bit Error Rate For Signals OFDM And Signal (8)

As it can be seen from the results of the experiment, noise stability of studied signals is virtually identical, that means orthogonal basis of signal (8) functions.

4.2 Noise immunity with additional subcarriers

An important feature of the signals is their ability adaptively to change the number of subcarriers at constant parameters of the selected frequency range at which the transmission of information occurs. In other words, during signal formation different value of frequency step between subcarriers can be used, moreover, the requirement $\Delta f = 1 / T$ is not obligatory. In this case, it is possible to increase the number of subcarriers that transmit information, providing the desired accuracy of the data reception. In the next study, the experiment was conducted to evaluate the maximum number of subcarriers that can be added to the signal without reducing its noise stability. The experimental results are presented in Figure 4 *a* and *b*. Signals 20 Mhz with bandwidth were used in the experiment. Duration of OFDM signals is12.8 µs while modeling signal transmission into channel is

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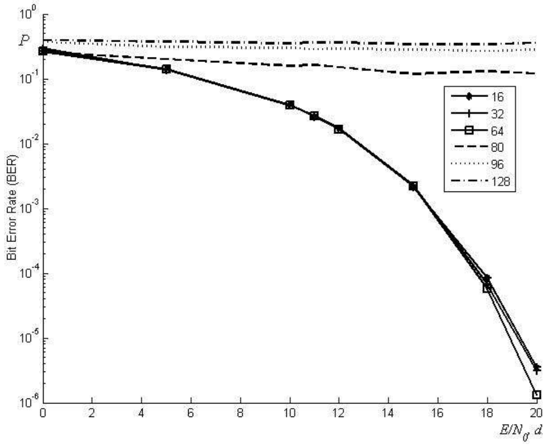
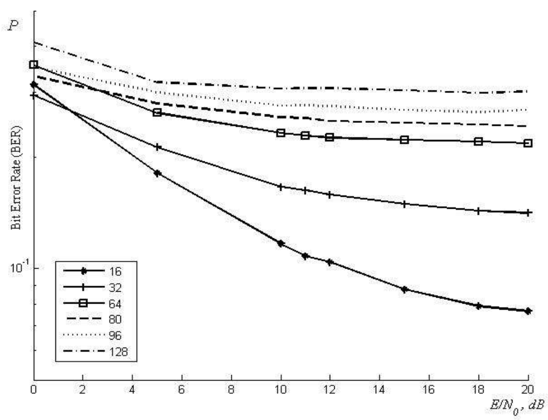
implemented consistently. Modulation on subcarriers is QAM-16. Signal duration (8) – 25.6 µs and signal transmission into channel is carried out with a rigid intersymbol interference with advance of 11.2 µs.



a)



b)

Figure 4. Bit Error Rate For Signals OFDM And Signal (7) With Variable Subcarrier:
A – Signal (8); B – Signal OFDM

The results for the numerical comparison of BER estimates, are placed in Table 2 – for signal (8) and in Table 3 for the OFDM signal. In cells of the table shows the values of BER estimation for different amounts of additional subcarriers and established ratio signal / noise ratio.

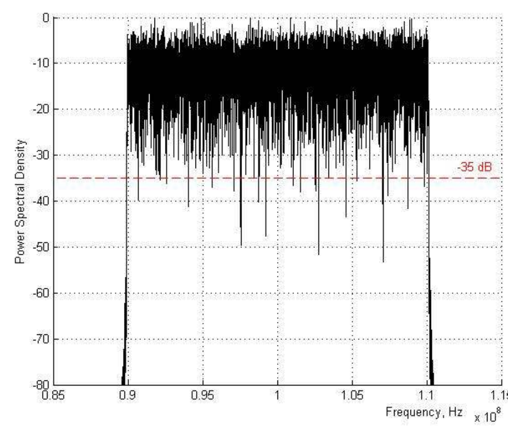
Table 1. BER Results For The Signal (8)

Table 2. BER Results For The Signal OFDM

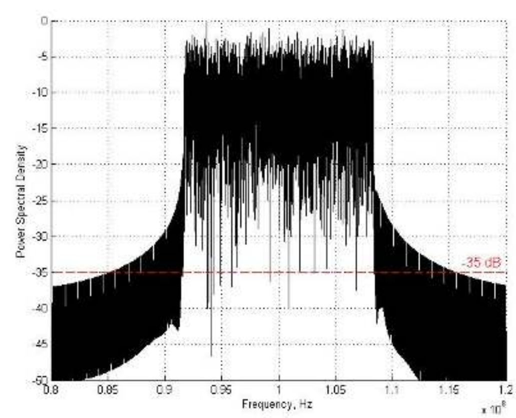
(S*ee in the appendix*)

Figures 4a and 4b show the difference between the noise immunity of the signals. The experimental results show that the proposed method of signal generation (8) allows to transmit 35% more data without compromising noise immunity, indicating its undeniable advantage over OFDM signals. In particular, regarding the results obtained for the signal with additional 64 subcarriers introduced therein. Its noise immunity did not change as can be seen from Tables 2 and 3, and the amount of information transmitted has increased by 35%.

The experimental results show that the proposed method of signal generation allows to transmit 35% information more without compromising noise stability, that indicates its absolute advantage over OFDM signals. It should be noted that the spectrum of the signal (8) with an additional 64 subcarriers has good localization of energy in the selected frequency channel (Figure 5) and does not exceed permissible standards (-35dB) unlike OFDM signal.



a)



b)

Figure 5. Frequency Spectrum Signal (8) With 64 Added Subcarrier:

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A – Signal (8); B – Signal OFDM

For the qualitative estimation of the frequency localization of signal of type (8), with the known analogs with no additional subcarriers the spectra were compared with the other signals such as the promising SMT, CMT signals. The goal of this experiment was to assess the level of localization of energy signals in the frequency domain with exactly the same parameters of the signal length and width of the occupied frequencies. The figure shows the compared signal sequences spectra consisting of 10 time frames with total duration of 256 ms, the frequency band is 20 MHz, and the modulation on the QAM-16 subcarriers.

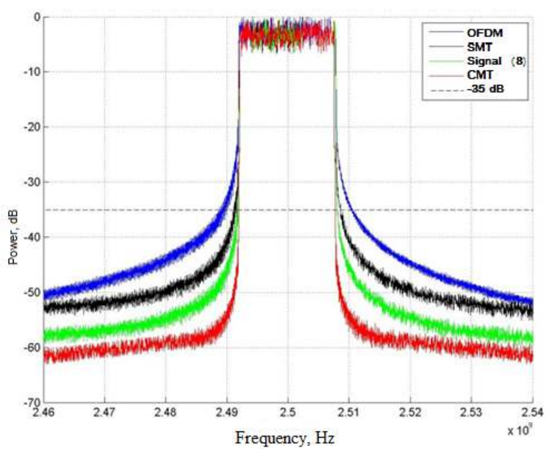

Figure 6. Frequency Spectrum Of Signals OFDM, SMT, CMT, Signal (8)

As seen from the figure, signal of type (8) has the advantage over the SMT signal as a shaping function of the signal (8) is better than the SMT function localized in the frequency domain. However, the signal of type (8) concedes the CMT signal, which can also be explained by the presence of subcarriers number two more than that of the CMT signal, but carrying only the real part of the transmitted symbols. However, the difference of 5 dB is not essential since in the real transmission conditions, the noise level in the channel is typically of 35 dB. As it was noted above a more detailed and comprehensive study of SMT and CMT signals is described in [11].

An additive white Gaussian noise with zero mean was used in the study of noise immunity, and it does not take into account a non-linear distortion occurring in the transmission path and the receiver. It should be noted that along with the advantages of the signal of type (8), the deterioration of its peak factor is also possible i.e. a peak to average power ration at the symbol interval time. However, the overall signal of the form (8), as shown in simulation is sufficiently many advantages over similar products.

5. CONCLUSION

As a result of the research we have is presented a new method of forming and signal processing with the ability to adaptively adjust the frequency-time parameters of the transmitted signal to the electromagnetic environment on the radio, while maximizing spectral efficiency and the required noise immunity. Taking into consideration these features signals class offered in the article absolutely meets the requirements for the use in advanced wireless communication systems such as 5G. The method of the signal generation offered in the article with the position of noise stability and spectral efficiency is compared with a known method of OFDM, which is today widely used in modern systems for wireless data transmission. As a result of comparison it is found that the new method of signal generation has 35% spectral efficiency more, because it is used for information transmission along with the main spectrum part of input intervals together with tighter location of subcarriers without lowering the noise stability of the transmitted signal. Also the offered approach allows not only to shape narrow areas of a spectrum in which it is necessary to provide absence of any frequency components, while providing set level of interference, but also adaptively change signal duration and a number of other parameters for optimum loading and distribution of channel resources of base radio network that is impossible to do using OFDM signals and his derivatives such as SMT and SMD. The research presented in this article make it possible to answer the scientific question about the possibility of transmission of information with the better spectral efficiency than OFDM signals at a given noise immunity provision.

These findings make it possible to suggest that the use of these signals in high-speed broadband 5G systems will allow to use the mechanisms of stochastic and adaptive use of network resources based on the detection of the available spectrum and its use on the principles of cognitive radio. This ensures their maximum capacity and spectrum efficiency in the radio channel. Given the fact that application of the developed type of signals is expected in broadband wireless access systems and 5G mobile communication, it is necessary to focus further studies on ability to work in a multipath channel with Rayleigh and Rician fading.

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Also very important factor is the use of advanced methods of information transmitted and signal processing using adaptive filtering (algorithms List Mean Square (LMS), Recursive Least Squares (RLS)) and sphere decoder. Within further investigations we plan to develop efficient method of processing with application of adaptive filtration of the signals offered in article, comparative assessment the signals FBMC, CMT and SMT c point of view of the complexity of the formation, as well as resistance to fading in the communication channel.

6. ACKNOWLEDGMENTS

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APPENDIX

Table 1. BER Results For The Signal (8)

E/N_0, dB	The number of additional subcarriers					
	16	32	64	80	96	128
0	0.66	0.62	0.6	0.61	0.5	0.5
5	0.78	0.78	0.78	0.70	0.5	0.5
10	0.039	0.04	0.04	0.71	0.5	0.5
12	0.08	0.08	0.08	0.71	0.5	0.5
15	0.007	0.007	0.007	0.73	0.5	0.5
18	0.00035	0.00033	0.00032	0.73	0.5	0.5
20	0.00005	0.000052	0.00008	0.73	0.5	0.5

Table 2. BER Results For The Signal OFDM

E/N_0, dB	The number of additional subcarriers					
	16	32	64	80	96	128
0	0.33	0.35	0.3	0.31	0.3	0.2
5	0.56	0.46	0.38	0.35	0.33	0.31
10	0.92	0.56	0.40	0.37	0.35	0.31
12	0.95	0.57	0.41	0.37	0.35	0.31
15	0.011	0.60	0.41	0.37	0.35	0.31
18	0.012	0.61	0.42	0.37	0.35	0.31
20	0.012	0.61	0.42	0.37	0.35	0.31