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QUASIORTHOGONAL FREQUENCY ACCESS ON SUBCARRIER FREQUENCIES

Abstract. In the article, it is described the principles of implementing the method based on quasiorthogonal frequency access on subcarrier frequencies. The key element of quasiorthogonal frequency access on subcarrier frequencies is the using of the individual distribution of frequency subcarriers in different frequency plans of the ensemble in the general frequency band, which allows increasing the subscriber capacity of the radio system significantly. It was developed an algorithm for the formation of the ensemble, taking into account the different values of the width of the subchannels in the corresponding frequency plans. It was graphically represented the form of frequency plans with different bandwidths and the dependence of the maximum emissions of the mutual correlation function of frequency plans, taking into account the number of subcarriers and the width of subchannels. For realization the statistical analysis, it was constructe an imitation model of the radio channel, it were graphically represented the results of statistical analysis of the interrelationship properties of frequency plans, and investigated the correlation properties of complex signals based on QOFDM. Using the quasiorthogonal access on subcarrier frequencies allows increasing the subscriber capacity of the communication system and the rate of information transmission due to the nonlinear distribution of the subcarrier frequencies.

Keywords: quasi-orthogonal frequency access on subcarrier frequencie; spectral hole; frequency collisions; bandwidth; frequency plan; an ensemble; the subscriber capacity.

Introduction

Formulation of the problem. The possibility of reusing the frequency resource under the low efficiency of its exploitation is a major advantage of cognitive radio systems, unlike current systems [1–3]. This can be achieved through the using of intelligent algorithms of training the cognitive radio systems. The introduction and operation of such systems raises the question of solving the problem of the implementation of the joint using of spectral holes by many users of the cognitive radio network [1, 4]. At simultaneous transmission of information by secondary users in the same free band of frequencies, the probability of occurrence of the phenomenon of so-called frequency collisions appears. In turn, this phenomenon can lead to the same before the appearance of a high level of internally systemic interference [5, 6].

To solve the existing problem, it was proposed to use the developed method based on quasiorthogonal frequency-division multiplexing (QOFDM).

Literature analysis. The existing orthogonal frequency-division multiplexing (OFDM) method can significantly increase the bandwidth of the wireless communication system [7]. However, with the dynamic change in the load in cognitive radio networks, the phenomenon of frequency collisions is possible, that is, the simultaneous occupation by different subscribers of the same frequency band that can cause an increase in the level of intra-system interference [1, 5].

An analysis of literary sources has shown that the topic of combating frequency collisions in cognitive radio systems is not sufficiently researched, therefore, the need to solve the problem of counteraction and prevention of such phenomena [8–14].

The aim of the article. The aim of the article is the detailed development of the method based on quasiorthogonal frequency access on subcarrier frequencies, which solves the problem of sharing many users of the cognitive radio system of the same frequency band. Solving this problem will significantly reduce the probability of occurrence of frequency collisions and will increase the subscriber capacity of the cognitive radio system.

Also, the aim of the article is to develop an algorithm for the formation of the ensemble, taking into account the different values of the width of subchannels in the corresponding frequency plans, developing a simulation model of the system of signals based on the QOFDM method and conducting research on the interrelation properties of the formed frequency plans based on quasiorthogonal access on subcarrier frequencies.

The basic material

It was proposed the method of quasiorthogonal frequency access on subcarrier frequencies based on the using of the individual distribution of the subcarriers for each frequency plan in the common band of frequencies. This method allows increasing the subscriber capacity of the cognitive radio system due to the parallel using of different subscribers of the same network of different variants of the distribution of high frequencies.

The ensemble of QOFDM signals consists of K number of frequency planes transmitted in the same frequency band ΔF. In this case, each frequency plan has an individual set of frequency subcarriers n, the distance between which Δf is equidistant, but each frequency plan has its own spacing value between the subcarrier frequencies, different from the spacing values in other frequency plans of the ensemble.

An analytical expression that describes quasiorthogonal frequency multiplexing of channels on subcarrier frequencies represents an improved OFDM signal formation equation and looks like this [15]:

$$S_i(\Delta f_i) = \\ = \mathrm{Re}\left\{ e^{j\cdot 2\cdot\pi\cdot f_0\cdot \Delta f_i} \cdot \sum_{k=-\Delta F/2}^{\Delta F/2} C_k \cdot e^{j\cdot 2\cdot\pi\cdot f\left(\Delta f_i - T_S\right)} \right\}, \quad (1)$$

where Δf_i – spacing interval frequency plan, Re – real part of a complex number; f_0 – zero sublime frequencies;

ΔF – band of frequencies; C_k – comprehensive presentation symbol QAM; T_s – the period of the signal.

Forming an ensemble algorithm [15] that is shown in Fig. 1 that consists of a sequence of such operations:

1. Determination of baseline data: the distance between subcarrier frequencies, frequency band; the number of subcarrier frequencies on the adjusted frequency band ΔF .
2. Formation. of all frequency plans in the ensemble with the adjusted parameters.

The distance between subcarrier frequencies for subcarrier frequencies for each frequency plan is calculated as the ratio of the frequency band *ΔF*, which takes the linear signal to the number of subcarrier frequencies in each frequency plan. The interval between subcarrier frequencies is calculated by the equation (2):

$$\Delta f_i = \Delta F / n_i \text{ , Hz} \qquad (2)$$

The distance between subcarrier frequencies for each frequency plan will be individual and will depend on the number of subcarrier frequencies in a specific frequency plan. The main difference between OFDM and QOFDM signals is that each QOFDM frequency plan is separately formed by the OFDM technology. That is, the interval between subcarrier frequencies is the same within this frequency plan. But in QOFDM there is a whole ensemble of signals, that is, a set of OFDM frequency planes that differ in different intervals distance between subcarrier frequencies. Herewith, the frequency band *ΔF* will be the same for the entire ensemble of signals.

3. Pairwise comparison of frequency plans for finding the positions that coincide.
4. Determination of the number of subcarrier frequency positions that coincide in each frequency plan.

By pairwise comparison of frequency plans with each other, the number of positions of frequency subcarriers that coincide in each frequency plan of the ensemble is determined. In this case, by comparing two frequency plans with each other, there will be no more than one frequency position that coincides.

K – the number of frequency plans in the ensemble, d_{ij} - the number of subcarrier frequency positions that coincided when comparing *i*-th frequency plan with *j*-th frequency plan.

5. Provided that if the number of positions of the subcarrier frequencies that coincided when the comparison of the *i*-th frequency plan with the *j*-th frequency plan will be more than or equal to the number of frequency plans in the ensemble ($d_{ij} \geq K$), there will be removal from the ensemble the *i*-th frequency plane. This will be the same frequency plan when compared with which there were most of the coincidences. After that again there is a pairwise comparison of frequency plans.
6. Provided that if the number of the subcarrier frequencies positions that coincided when compared the *i*-th frequency plan with the *j*-th frequency plan will be less than the number of frequency plans in the ensemble ($d_{ij} < K$), the *i*-th frequency plan will be added to the ensemble.
7. Frequency plan is added to the ensemble.
8. The ensemble is accepted for further synthesis of signals.

Selected frequency plans form an ensemble that is accepted for further synthesis of signals.

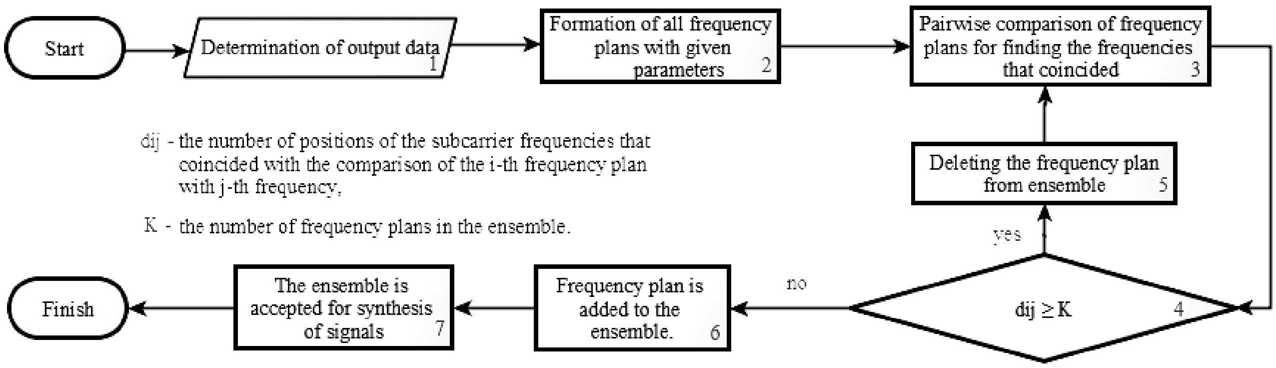

Fig. 1. The algorithm of forming the ensemble of signals

For illustrating the robustness of the proposed method, an example is presented in which four frequency plans with different amounts of subcarrier frequencies are presented, that is:

$$n_1 = 23,\ n_2 = 101,\ n_3 = 187,\ n_4 = 259 .$$

All frequency plans are transmitted in the same frequency band

$$\Delta F = 20 \text{ MHz} .$$

Based on the given parameters, it can be possible to calculate the intervals between the positions of the subcarrier frequencies in the frequency domain for each plan, using the equation (2).

The positions of the subcarrier frequencies that coincided with the comparison of the first and second, first and third, first and fourth signals are indicated by violet rectangles, as shown in Fig. 2.

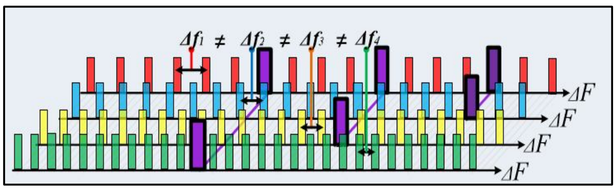

Fig. 2. Subcarrier frequencies distribution scheme for QOFDM

Fig. 3 shows the subcarrier frequencies positions that coincided when compared the frequency plans pairwise with each other. The positions that coincide are marked by yellow rectangles.

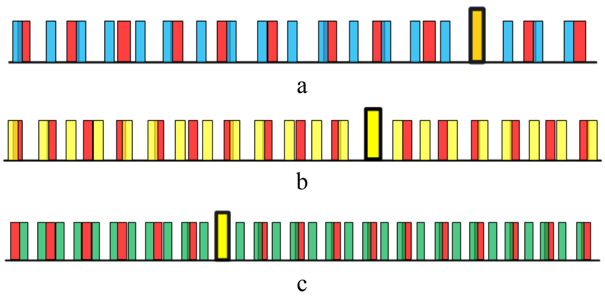

Fig. 3. The subcarrier frequencies positions that coincided when compared pairwise with each other: a – 1- st and 2-nd frequency plans, b – 1- st and 3-rd frequency plans, c – 1- st and 4-th frequency plans

Results of simulation of four frequency plans are listed in Table 1.

Table 1 – **The results of the subcarrier frequencies distribution in the ensemble from the four frequency plans**

Parameter Value		Amount			
		K_1	K_2	K_3	K_4
The width of the frequency band, Hz		2010^6	$20*10^6$	$20*10^6$	$20*10^6$
The number of sub-carrier frequencies n_i		23	101	187	259
The interval between subcarrier frequencies, Hz	Min	859570	188020	96950	67220
	Max	869470	192790	106850	77120
The subchannel width, Hz	Min	100	100	100	100
	Max	15000	15000	15000	15000

In order to evaluate the possibilities of using the frequency resource under the condition of using quasiorthogonal access on subcarrier frequencies, it is necessary to research the degree of influence of systemic interferences when changing the bandwidth of subchannels between different frequency plans. A model of the channel was constructed, in which for the 4 values of the number of subchannels the degree of mutual correlation between them changed. The degree of similarity of frequency plans was estimated by calculating the function of mutual correlation [9–14]. The mathematical mechanism is implemented on the basis of correlation analysis.

The dependence of the maximum emissions of side lobes of the mutual correlation function of frequency plans at different values of the width of the subchannel bands and the number of subcarrier frequencies in frequency plans is shown in Fig. 4.

Fig. 4 shows with the changing of the subchannel width and the number of subcarrier frequencies in the frequency plan *Ki*, the value of the level of mutual correlation between frequency plans increases, but does not exceed the permissible value for the two compared processes $B_{ij} = 5 / Ki$. [5].

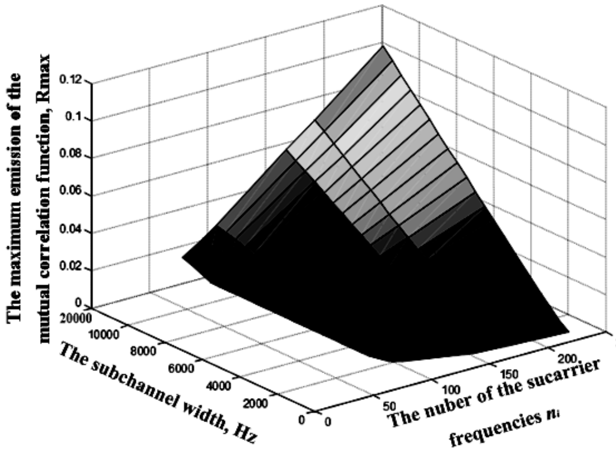

Fig. 4. The dependence of the maximum emissions of the mutual correlation function of frequency plans at different values of the width of the subchannel bands and the number of subcarrier frequencies

In order to optimize the frequency plan formation mechanism, it is necessary to evaluate the statistical characteristics of the signal parameters on the basis of QOFDM. It was performed a statistical analysis of the correlation properties of the complex signals generated on the basis of quasiorthogonal access on subcarrier frequencies. The research results of the properties of such signals allow optimizing the process of selecting the signal parameters that increase the volume of ensemble signals at low interaction in the frequency domain.

It was used a classical method for evaluating statistical characteristics, described in [4] in order to evaluate the statistical characteristics of the correlation properties of the ensemble of the complex signals formed on the basis of QOFDM.

Calculation of the mathematical expectation (ME) of maximum emission of side lobes of the mutual correlation functions [max R_{ij}] of two comparable frequency plans *i* and *j* [15–17]:

$$m[\max B_{ij}] = \sum_{k=1}^{N} \left|\max B_{ij}(k)\right| \Big/ N, \qquad (3)$$

where N – the number of interacting signals pairs; $\max B_{ij}$ – the maximum emissions of side lobes of the mutual correlation function.

Calculation of mean-square deviations (MSD) of maximum emissions of side lobes of the mutual correlation function $\sigma_{\max}$ of two comparable frequency plans *i* and *j* [15–17]:

$$\sigma_{\max B_{ij}} = \sqrt{\sum_{k=1}^{N} \left(\left|\max B_{ij}(k)\right| - m\left[\max B_{ij}\right]\right)^2 \Big/ N}. \qquad (4)$$

The research results are presented in Fig. 5.

It is seen from Figure 5 with increasing the width of the band of subchannels in each frequency plan the level of mutual correlation of frequency plans deteriorates, however, the values of maximum emission of side lobes of the mutual correlation function remain within the confidence interval and slightly different from the condition of the minimum similarity of the frequency plans [5]:

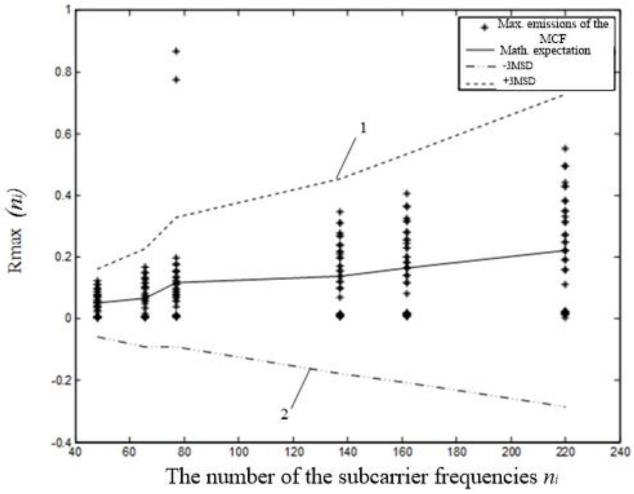

Fig. 5. Results of statistical analysis of intercorrelation properties of frequency plans

$$B_{ij} = (1 \div 5) \Big/ \sqrt{N_i N_j} \, . \qquad (5)$$

Thus, even with increasing bandwidth to the limit value inherent in the IEEE 802.20 protocol, i.e. 15 kHz, the degree of mutual correlation of frequency plans will be satisfactory. In the future, it is necessary to evaluate the characteristics on the basis of QOFDM when using different modulation formats in difficult obstacle conditions.

Conclusions

In the article, it was developed in details a method based on quasiorthogonal frequency access on subcarrier frequencies that solves the problem of common using by many users of cognitive radio systems of the same frequency band. Solving this problem can significantly reduce the number of frequency collisions and increase the subscriber capacity of the cognitive radio system.

It was developed an algorithm for the formation of the ensemble, taking into account the different values of the width of the subchannels in the corresponding frequency plans.

It was developed the simulation model of the signal system based on the QOFDM method.

It was performed the research of the correlation properties of the generated frequency plans based on quasiorthogonal access on subcarrier frequencies. Due to the nonlinear distribution of subcarrier frequencies in different frequency plans of one ensemble of signals, the subscriber capacity significantly increases, while there is a probability of a slight deterioration in the quality of the information transmission.

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Квазіортогональний частотний доступ на піднесних частотах

Ю. О. Свергунова, М. А. Штомпель, В. П. Лисечко, І. В. Ковтун

В статті представлено принципи реалізації методу на основі квазіортогонального частотного доступу на піднесних частотах. Ключовим елементом квазіортогонального частотного доступу на піднесних частотах є використання індивідуального розподілу частотних піднесних в різних частотних планах ансамблю в загальній смузі частот, яке дозволяє значно збільшити абонентську ємність радіосистеми. Було розроблено алгоритм формування ансамблю із врахуванням різного значення ширини підканалів у відповідних частотних планах. Графічно представлено вигляд частотних планів при різній ширині смуги частот та залежності максимальних викидів функції взаємної кореляції частотних планів із врахуванням кількості піднесних та ширини підканалів. Для здійснення статистичного аналізу було побудовано імітаційну модель радіоканалу, графічно представлені результати статистичного аналізу взаємокореляційних властивостей частотних планів, досліджено кореляційні властивості складних сигналів на основі QOFDM. При застосуванні квазіортогонального доступу на піднесних частотах збільшиться абонентська ємність системи зв'язку та швидкість передачі інформації завдяки нелінійному розподілу піднесних частот.

Ключові слова: квазіортогональний частотний доступ на піднесних частотах; спектральні діри; частотні колізії; смуга частот; частотний план; ансамбль; абонентська ємність.

Квазиортогональный частотный доступ на поднесущих частоты

Ю. А. Свергунова, Н. А. Штомпель, В. П. Лысечко, И. В. Ковтун

В статье представлены принципы реализации метода на основе квазиортогональных частотного доступа на поднесущих частотах. Ключевым элементом квазиортогональных частотного доступа на поднесущих частотах является использование индивидуального распределения частотных поднесущих в различных частотных планах ансамбля в общей полосе частот, которое позволяет значительно увеличить абонентскую емкость радиосистемы. Был разработан алгоритм формирования ансамбля с учетом разного значения ширины подканалов в соответствующих частотных планах. Графически представлены вид частотных планов при различной ширине полосы частот и зависимости максимальных выбросов функции взаимной корреляции частотных планов с учетом количества поднесущих и ширины подканалов. Для осуществления статистического анализа было построено имитационную модель радиоканала, графически представлены результаты статистического анализа взаимнокорреляционных свойств частотных планов, исследованы корреляционные свойства сложных сигналов на основе QOFDM. При применении квазиортогональных доступа на поднесущих частотах увеличится абонентская емкость системы связи и скорость передачи информации, благодаря нелинейной распределения поднесущих частот.

Ключевые слова: квазиортогональный частотный доступ на поднесущих частотах; спектральные дыры; частотные коллизии; полоса частот; частотный план; ансамбль; абонентская емкость.