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## METHOD OF SYSTEMATIC CHANNEL-BLOCK PERMUTATIONS IN A QOFDM SIGNAL ENSEMBLE

### Introduction

The growing demand for wireless data transmission increases the load on radio-frequency resources and complicates the organization of access in shared spectral environments. This problem is especially relevant for cognitive radio systems, where temporarily available frequency intervals may be used by secondary users. If several users operate within the same available band, the structure of multicarrier signals must be organized so that frequency coincidences and intra-system interaction are limited at the stage of signal-ensemble formation.

One possible approach to this problem is the use of QOFDM frequency-plan ensembles. In such ensembles, a common frequency band is represented not by a single allocation scheme, but by a set of frequency plans with different numbers of subcarriers. Each plan has its own subcarrier spacing, while all plans remain within the same total bandwidth. This construction allows the same spectral interval to be used through several coordinated frequency plans and forms the basis for quasi-orthogonal access on subcarrier frequencies.

However, the formation of frequency plans does not fully determine the internal structure of channel use inside the ensemble. After the subcarrier positions have been defined, logical channels must still be assigned to groups of frequency positions within each plan. If this assignment remains identical for all plans, the same logical channel may repeatedly occupy corresponding relative blocks in different frequency plans. In a discrete structural representation, this can concentrate coincident frequency positions inside the same logical channel.

The considered problem therefore belongs not to the synthesis of new subcarrier positions, but to the

organization of channel ownership over already formed QOFDM plans. The base QOFDM construction determines the subcarrier spacing, subcarrier positions, and admissibility condition of the ensemble. The additional question is whether the mapping between logical channels and frequency-position blocks can be systematically varied from plan to plan without changing these base quantities.

This article develops QOFDM-SP as a structural extension of QOFDM. The method introduces systematic inter-plan permutations of logical channel assignments over frequency-position blocks. The proposed assignment layer does not form a new physical-layer signal and does not modify the subcarrier spacing, subcarrier positions, or threshold admissibility condition of the base QOFDM ensemble. Its purpose is to redistribute existing discrete frequency coincidences between logical channels, reduce accumulated same-channel structural coincidences, and improve the uniformity of channel-wise frequency-position coverage.

### Analysis of recent research and publication

The analysis of publications, standards, and recommendations [1–15] indicates that the problem of efficient frequency-resource use in wireless and cognitive radio systems is studied at several related levels: cognitive radio principles, spectrum sensing and spectrum assignment, multicarrier access, frequency-plan formation, and subcarrier/resource allocation. At the same time, these studies mainly address spectrum access, frequency-plan synthesis, correlation properties, or resource allocation in OFDM/OFDMA-based systems, whereas the QOFDM-specific problem of systematic channel-block reassignment inside already formed frequency plans is not explicitly addressed in the cited sources.

The general conceptual basis for cognitive radio was introduced in [4], where radio systems are considered as adaptive software-defined entities capable of more flexible interaction with the radio environment. Further development of this direction is presented in [5], where cognitive radio, software-defined radio, and adaptive wireless systems are considered as a common technological framework for dynamic spectrum use. Network-level aspects of cognitive radio communications, including access organization and coexistence problems, are summarized in [6]. Spectrum sensing, which is one of the key prerequisites for detecting available frequency resources in cognitive radio systems, is reviewed in [12]. These works form the general background for the use of spectral holes and adaptive access mechanisms, but they do not consider the internal channel-block structure of QOFDM frequency-plan ensembles.

A separate group of studies is devoted to spectrum assignment, aggregation, and sharing in cognitive radio networks. A comprehensive survey of spectrum assignment methods is presented in [7], where the allocation of available spectrum resources is treated as a network-level coordination problem. Small-scale spectrum aggregation and sharing mechanisms are considered in [8], while dynamic spectrum aggregation for future 5G communications is analyzed in [9]. The IEEE 802.22 cognitive radio wireless regional area network standard is discussed in [10] as an example of standardized cognitive radio operation. These studies are important for understanding the broader problem of shared spectrum use, but their focus is the allocation or aggregation of spectrum resources rather than the permutation of logical-channel ownership within QOFDM frequency plans.

Multicarrier and OFDM-based approaches also provide a relevant comparative context. In [11], an OFDM-based virtual clustering scheme is proposed for distributed coordination in cognitive radio networks, which confirms the importance of multicarrier structures for coordinated access. Recommendation [13] describes radio interface standards for broadband wireless access systems, including mobile and nomadic applications, and therefore represents the standardization context of broadband multicarrier access. In LTE, physical-channel and modulation principles are specified in [14], including resource mapping mechanisms used in E-UTRA systems. Interleaved block subcarrier allocation for OFDMA systems is investigated in [15], where subcarrier allocation is used as part of a multiuser allocation mechanism. These works demonstrate that subcarrier distribution, interleaving, and resource mapping are important mechanisms in multicarrier systems.

However, they are not direct analogues of QOFDM-SP, because QOFDM-SP does not perform standard OFDMA scheduling and does not change the physical subcarrier positions.

QOFDM-specific research is represented by [1–3]. In [1], quasiorthogonal frequency access on subcarrier frequencies is developed through the formation of frequency-plan ensembles with different numbers of subcarriers in a common frequency band. The earlier work [2] presents the method of quasiorthogonal frequency multiplexing on subcarrier frequencies and forms one of the initial bases for this direction. In [3], recovery errors and correlation-related properties of QOFDM signals are analyzed, which confirms the importance of parameter selection and signal-level effects in QOFDM-based systems. Thus, QOFDM research is mainly concentrated on the construction of frequency plans, mutual-correlation behavior, and signal recovery aspects.

Therefore, the cited publications, standards, and recommendations [1–15] form the necessary scientific and technical background for the considered problem. However, they do not explicitly introduce a QOFDM-specific channel-block assignment layer in which the base QOFDM subcarrier positions remain unchanged while the mapping of logical channels to frequency-position blocks is systematically varied between plans. This unresolved structural aspect defines the narrower problem addressed in the present article.

### Problem Statement

Let a QOFDM frequency-plan ensemble already be defined. In the general QOFDM formulation, admissibility is evaluated by the threshold mutual-correlation condition. The present article does not revise this construction. The  $K = 24$  ensemble used below is treated as an author-defined reproducible structural test ensemble rather than as a fully validated admissible QOFDM ensemble under the complete mutual-correlation admissibility model. In such an ensemble, every frequency plan has its own number of subcarriers in the common frequency band, and the corresponding subcarrier spacing and positions are determined by the base QOFDM construction [1, 2]. The present article does not revise this construction.

The QOFDM-SP problem appears after the frequency plans have already been formed. If logical channels are assigned to the same relative blocks of every plan, then coincident frequency positions can remain assigned to the same logical channel in both plans. In a discrete structural description, such coincidences are considered potentially harmful same-channel coincidences.

The task is therefore to define a reproducible channel-block assignment procedure that changes only the mapping between logical channels and subcarrier blocks. The base subcarrier spacing, the base subcarrier positions, and the threshold admissibility condition of the QOFDM ensemble are preserved. The model mutual-correlation quantity used for QOFDM admissibility, an auxiliary discrete coincidence count, and the structural same-channel metric introduced in this work are treated as distinct quantities.

### The purpose of the article

The purpose of the article is to develop and verify a new structural QOFDM-SP assignment method as a further development of QOFDM. The method introduces systematic channel-block permutations over already formed QOFDM frequency plans and is evaluated by structural indicators of same-channel coincidences and channel-wise frequency-position distribution uniformity.

### Summary of the main material

The proposed method is applied after the QOFDM frequency plans have already been formed. Therefore, the summary of the main material starts from the additional channel-block assignment layer introduced in QOFDM-SP, without re-deriving the base QOFDM relations.

For each frequency plan, the ordered set of subcarrier positions is divided into  $L$  contiguous blocks. For  $L = 4$ , these blocks are interpreted as candidate frequency-position blocks for four logical channels. The first  $L - 1$  block sizes are:

$$m_{i,\ell} = \left\lfloor \frac{n_i}{L} \right\rfloor, \quad \ell = 1, \dots, L - 1, \quad (1)$$

and the last block absorbs the remainder:

$$m_{i,L} = n_i - (L - 1) \left\lfloor \frac{n_i}{L} \right\rfloor. \quad (2)$$

For every plan  $i$ , QOFDM-SP method introduces a permutation:

$$\pi_i \in S_L, \quad (3)$$

where  $S_L$  is the symmetric group of all channel-block permutations.

The assignment matrix is:

$$\Pi = \begin{bmatrix} \pi_1(1) & \cdots & \pi_1(L) \\ \vdots & \ddots & \vdots \\ \pi_K(1) & \cdots & \pi_K(L) \end{bmatrix} \quad (4)$$

The identity strategy corresponds to the base fixed assignment. The cyclic strategy shifts the assignment by one channel from plan to plan. The all-factorial strategy starts with cyclic rows and then uses the ordered set of all permutations from  $S_L$ . For  $L = 4$ ,  $|S_4| = 24$ ; therefore, the  $K = 24$  experiment uses each permutation exactly once in the all-factorial strategy.

Table 1 summarizes the difference between base QOFDM assignment and QOFDM-SP. The comparison emphasizes that QOFDM-SP does not redefine the physical structure of the frequency plans. The subcarrier spacing, subcarrier positions, and threshold admissibility condition remain inherited from the base QOFDM ensemble, whereas the proposed method adds only the channel-to-block assignment layer. Therefore, the essential distinction is not in the formation of new subcarrier positions, but in the systematic permutation of logical channel ownership across already formed plans.

Fig. 1 shows the structural workflow used in the numerical experiment. In the general formulation, QOFDM-SP is applied after the QOFDM frequency plans have already been defined. In the present  $K=24$  experiment, the input is the author-defined prime structural test ensemble, after which each plan is divided into logical channel blocks, the assignment matrix is constructed, one of the considered permutation strategies is applied, and the resulting structural metrics are evaluated.

Table 1

Conceptual comparison of base QOFDM assignment and QOFDM-SP

Feature	Fixed assignment over base QOFDM plans	QOFDM-SP assignment
Subcarrier spacing $\Delta f_i$	Defined by $\Delta F/n_i$	Unchanged
Subcarrier positions $f_{i,k}$	Defined by $k\Delta f_i$	Unchanged
Threshold admissibility condition	Uses $B_{ij}^{(\text{mod})}$	Unchanged
Channel-to-block mapping	Fixed across plans	Permuted between plans
Assignment operator	Not introduced	Provided by $\pi_i \in S_L$
Structural metric $J$	Not used for assignment	Used to count same-channel structural coincidences

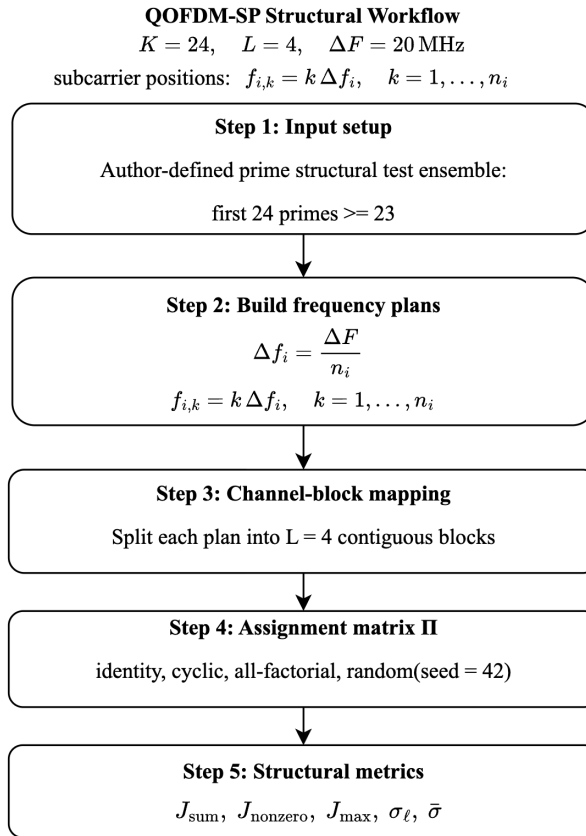


Fig. 1. QOFDM-SP structural workflow

The diagram also separates the preserved QOFDM components from the additional QOFDM-SP procedure. This is important because the proposed method acts after frequency-plan formation and affects only the mapping between logical channels and frequency-position blocks. The subsequent subsection formalizes the metrics used to evaluate this structural redistribution.

### Structural metrics

A frequency coincidence between plans  $i$  and  $j$  is a pair of subcarrier indices for which:

$$f_{i,k} = f_{j,m}. \quad (5)$$

The structural harmful-coincidence count for a pair of plans is:

$$I_{ij}^{(\text{ch})} = \left| \left\{ \begin{array}{l} (k, m): f_{i,k} = f_{j,m} \\ \text{ch}_i(k) = \text{ch}_j(m) \end{array} \right\} \right|, \quad (6)$$

where  $\text{ch}_i(k)$  is the logical channel assigned to the  $k$ -th subcarrier of plan  $i$ . The main maximum metric is:

$$J(\Pi) = \max_{i \neq j} I_{ij}^{(\text{ch})}. \quad (7)$$

The maximum value in (7) is further denoted as  $J_{\max}$  when the worst-case same-channel coincidence count is discussed. To characterize the accumulated structural effect of an assignment strategy, the following additional metrics are also used:

$$J_{\text{sum}} = \sum_{i < j} I_{ij}^{(\text{ch})}, \quad (8)$$

$$J_{\text{nonzero}} = \left| \{(i, j): I_{ij}^{(\text{ch})} > 0, i < j\} \right|. \quad (9)$$

For channel-wise frequency-position distribution, the frequency band is partitioned into equal histogram intervals. For each logical channel  $\ell$ ,  $\sigma_\ell$  is the standard deviation of the corresponding histogram counts. The mean channel-distribution metric is:

$$\bar{\sigma} = \frac{1}{L} \sum_{\ell=1}^L \sigma_\ell. \quad (10)$$

The metric  $J$  is a discrete structural metric. It is not a replacement for  $B_{ij}^{(\text{mod})}$ , and it does not measure the same object as an auxiliary coincidence count  $c_{ij}$ .

### $K = 24$ reproducible ensemble

The experiment uses:

$$\begin{aligned} K &= L! = 4! = 24, \\ L &= 4, \Delta F = 20 \text{ MHz}. \end{aligned} \quad (11)$$

The values  $n_i$  are the first 24 prime integers greater than or equal to 23:

$$\left\{ \begin{array}{l} 23, 29, 31, 37, 41, 43, 47, 53, \\ 59, 61, 67, 71, 73, 79, 83, 89, \\ 97, 101, 103, 107, 109, 113, \\ 127, 131 \end{array} \right\}. \quad (12)$$

The selected set of prime-valued frequency plans forms an author-defined reproducible structural test ensemble. The ensemble is used for evaluating channel-block permutation effects and is not claimed to constitute a fully validated admissible QOFDM ensemble under the complete mutual-correlation admissibility model. Full validation of  $B_{ij}^{(mod)}$  for the selected prime ensemble remains a limitation of the present work.

Since all  $n_i$  are pairwise coprime, every pair of plans has only the endpoint coincidence at  $f = \Delta F$ . Therefore,  $J_{max}$  is already equal to 1 for all tested assignment strategies. The main comparison is consequently based on  $J_{sum}$ ,  $J_{nonzero}$ , and  $\bar{\sigma}$ , not on a reduction of  $J_{max}$ .

Table 2 presents the numerical comparison of the considered assignment strategies for the selected  $K = 24$  structural ensemble. Since the maximum harmful-coincidence value  $J_{max}$  remains equal to 1 for all strategies, it is not used as a comparative column in this table. Instead, the comparison focuses on the accumulated number of same-channel coincidences  $J_{sum}$ , the number of plan pairs with nonzero

same-channel coincidences  $J_{nonzero}$ , and the mean channel-distribution standard deviation  $\bar{\sigma}$ .

These metrics characterize different aspects of the same structural redistribution process. The values  $J_{sum}$  and  $J_{nonzero}$  show how many endpoint coincidences remain assigned to the same logical channel after applying a strategy, whereas  $\bar{\sigma}$  describes the uniformity of the channel-wise frequency-position distribution.

The table shows that the identity assignment preserves same-channel coincidences for all plan pairs, whereas cyclic and all-factorial assignments reduce the accumulated and nonzero-pair coincidence metrics to the same level. The random strategy gives an intermediate result. Therefore, the distinction between cyclic and all-factorial assignment in this experiment is expressed mainly through  $\bar{\sigma}$  and through the construction principle of the assignment matrix, not through  $J_{max}$ .

To complement the numerical comparison, Fig. 2 visualizes how the channel-wise frequency-position distribution changes when the fixed identity assignment is replaced by the all-factorial assignment.

Table 2

Strategy comparison for the K=24 structural ensemble

Strategy	$J_{sum}$	$J_{nonzero}$	$\bar{\sigma}$
identity	276	276/276	7,63
cyclic	60	60/276	1,09
all-factorial	60	60/276	1,29
random(seed = 42)	71	71/276	2,36

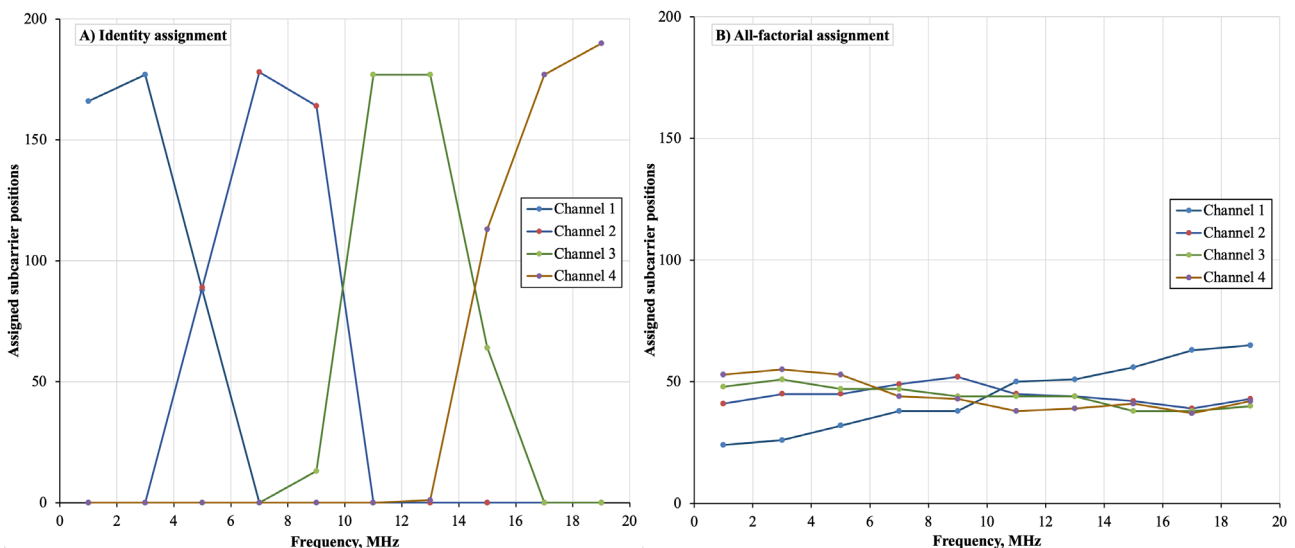


Fig. 2. Channel-wise frequency-position distribution for identity and all-factorial assignment in the  $K = 24$  QOFDM-SP structural ensemble. Counts are aggregated over 2 MHz intervals for visualization

Fig. 2 illustrates the redistribution effect visually. In the identity case, each logical channel remains concentrated in a fixed relative part of the band. In the all-factorial case, channel ownership is redistributed between plans, and the frequency-position counts

become more uniform across the four logical channels. This visual result is consistent with the decrease of  $\bar{\sigma}$  from 7.63 to 1.29 for the all-factorial assignment.

The channel-wise distribution metric shows a different ordering. In this experiment, the cyclic assignment gives the lowest  $\bar{\sigma} = 1.09$ , while the all-factorial strategy gives  $\bar{\sigma} = 1.29$ . Therefore, the all-factorial strategy is not presented as the strongest strategy according to every metric. It is considered structurally relevant because, for  $L = 4$  and  $K = 24$ , it provides complete one-time coverage of all 24 permutations from  $S_4$ .

Table 3 details the channel-wise components of the distribution-uniformity metric for the identity and all-factorial assignments. The table is included to show how this complete permutation-coverage strategy changes the per-channel values of  $\sigma_\ell$  relative to the fixed identity assignment.

Table 3

**Channel-wise sigma for identity and all-factorial  
( $K = 24$ )**

Article channel	$\sigma_\ell$ , identity	$\sigma_\ell$ , all-factorial	Relative decrease
1	7,57	1,70	77,5 %
2	7,56	1,18	84,4 %
3	7,39	1,08	85,4 %
4	8,02	1,22	84,8 %
Mean	7,63	1,29	83,0 %

The values in Table 3 show that the all-factorial assignment decreases  $\sigma_\ell$  for each logical channel relative to the identity assignment. The mean decrease from 7,63 to 1,29 confirms that the permutation-based assignment improves the uniformity of channel-wise frequency-position coverage in the considered structural model.

Thus, the developed QOFDM-SP method acts as an additional structural control layer. Its expected effect is not a change in the admissibility of the base QOFDM ensemble, but a redistribution of existing frequency-position coincidences between logical channels. Therefore, the improvement is evaluated by the accumulated same-channel coincidence metric  $J_{\text{sum}}$ , the number of nonzero same-channel plan pairs  $J_{\text{nonzero}}$ , and the channel-wise distribution-uniformity metric  $\bar{\sigma}$ .

### Conclusions

The article presents QOFDM-SP as a structural development of QOFDM that adds systematic channel-block assignment permutations over already formed frequency plans. The method preserves the QOFDM subcarrier spacing, subcarrier positions, and threshold admissibility condition.

For the author-defined  $K = 24$  prime ensemble with  $L = 4$  and  $\Delta F = 20$  MHz, all selected  $n_i$  values are pairwise coprime. Therefore, each pair of plans has one endpoint coincidence at  $f = \Delta F$ .

The main structural result is the reduction of accumulated same-channel coincidences. Both cyclic and all-factorial assignments reduce  $J_{\text{sum}}$  from 276 to 60 and  $J_{\text{nonzero}}$  from 276/276 to 60/276. The cyclic assignment gives the lowest mean channel-distribution standard deviation in this experiment. The all-factorial strategy remains structurally relevant because, for  $K = 24$  and  $L = 4$ , it uses each permutation from  $S_4$  exactly once.

The study is limited to structural frequency-position coincidences and histogram-based channel distribution metrics. Validation of the full QOFDM admissibility condition and signal-level performance requires separate modelling.

Therefore, within the considered structural model, the proposed QOFDM-SP method improves the distribution of logical-channel assignments by reducing accumulated same-channel coincidences and by providing a more uniform channel-wise frequency-position coverage, without changing the underlying QOFDM frequency plans.

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**Харченко І. В., Лисечко В. П.**

## **МЕТОД СИСТЕМАТИЧНИХ КАНАЛЬНО-БЛОЧНИХ ПЕРЕСТАНОВОК В АНСАМБЛІ СИГНАЛІВ QOFDM**

У статті QOFDM-SP (Subcarrier Permutation) представлено як подальший розвиток квазіортогонального частотного доступу на піднесучих частотах. Метод не вводить новий сигнал фізичного рівня та не змінює частотні плани, крок між піднесучими, позиції піднесучих або порогову умову допустимості базового ансамблю QOFDM.

Запропонований метод додає систематичний рівень канално-блочного призначення над уже визначеними частотними планами. На цьому рівні кожний частотний план поділяється на логічні каналні блоки, а призначення каналів до цих блоків змінюється між планами за допомогою перестановок. Відтворюваний структурний експеримент виконано для ансамблю з параметрами  $K = 24$ ,  $L = 4$ ,  $\Delta F = 20$  МГц. Вибрані значення кількості піднесучих є першими 24 простими цілими числами, не меншими за 23.

Оскільки ці значення є попарно взаємно простими, кожна пара планів має один крайовий збіг на верхній межі спільної смуги, а максимальна кількість збігів у межах одного каналу залишається рівною одиниці для всіх протестованих стратегій. Тому основний структурний ефект спостерігається в накопиченій кількості збігів у межах одного каналу та в кількості пар планів із такими збігами: як циклічне, так і повнофакторіальне призначення зменшують ці значення з 276 до 60 та з 276/276 до 60/276 відповідно.

Таким чином, у межах прийнятої дискретної структурної моделі запропонований метод QOFDM-SP забезпечує більш рівномірну канално-блочну організацію ансамблів сигналів QOFDM та зменшує концентрацію внутрішньоканальних збігів частотних позицій без модифікації базових частотних планів QOFDM.

**Ключові слова:** QOFDM, квазіортогональний частотний доступ, позиції піднесучих, канално-блочне призначення, перестановки, структурні збіги, частотні плани.

**Kharchenko I., Lysechko V.**

## **METHOD OF SYSTEMATIC CHANNEL-BLOCK PERMUTATIONS IN A QOFDM SIGNAL ENSEMBLE**

The article presents QOFDM-SP (Subcarrier Permutation) as a further development of quasiorthogonal frequency access on subcarrier frequencies. The method does not introduce a new physical-layer signal and does not change the frequency plans, subcarrier spacing, subcarrier positions, or threshold admissibility condition of the base QOFDM ensemble.

The proposed method adds a systematic channel-block assignment layer over already defined frequency plans. In this layer, each frequency plan is divided into logical channel blocks, and the assignment of channels to these blocks is varied

between plans by permutations. A reproducible structural experiment is performed for an ensemble with  $K = 24$ ,  $L = 4$ ,  $\Delta F = 20$  MHz. The selected values of the number of subcarriers are the first 24 prime integers not smaller than 23.

Since these values are pairwise coprime, each pair of plans has one endpoint coincidence at the upper edge of the common band, and the maximum same-channel coincidence count remains equal to one for all tested strategies. The main structural effect is therefore observed in the accumulated number of same-channel coincidences and in the number of plan pairs with such coincidences: both the cyclic and all-factorial assignments reduce these values from 276 to 60 and from 276/276 to 60/276, respectively.

Thus, within the adopted discrete structural model, the proposed QOFDM-SP method provides a more uniform channel-block organization of QOFDM signal ensembles and reduces the concentration of same-channel frequency-position coincidences without modifying the base QOFDM frequency plans.

**Keywords** QOFDM, quasiorthogonal frequency access, subcarrier positions, channel-block assignment, permutations, structural coincidences, frequency plans.

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