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THE USE OF SDR AS SENSOR NODES OF THE INTELLIGENT SYSTEM OF MANAGEMENT OF RADIO EMISSION DATA COLLECTION

Макаренко А., Отрох С. Використання SDR в якості сенсорних вузлів інтелектуальної системи управління мережею збору даних радіовипромінювання. Стаття присвячена дослідженню використання програмно керованого радіо (SDR) в контексті зростаючого попиту на безпроводові технології та радіоелектронні пристрої. Вона акцентує увагу на проблемах перенасиченості радіоспектра, потреби в автоматизації управління радіосистемами, забезпеченні безпеки, використанні машинного навчання та ШІ, інтеграції різних систем, а також на економічних вигодах. Стаття розглядає SDR як інструмент для вирішення цих викликів, особливо через його здатність працювати на широкому діапазоні частот і використання цифрової обробки сигналів. Також розкривається роль ПКР в радіомоніторингу та його важливість у виявленні та усуненні джерел завад.

Основна увага приділяється розробці алгоритму виконання операцій OFDM-модуляції в SDR інтелектуальних систем управління мережею збору даних радіовипромінювання. Пропонований алгоритм має на меті оптимізувати передачу даних, зменшуючи передачу надлишкових біт інформації та сприяючи ефективному використанню радіоспектра. В статті детально описано архітектуру та функціональні можливості SDR, включаючи аналіз впливу технологій OFDM на ефективність передачі даних в рамках програмно керованих систем.

Стаття описує наступні етапи розробки алгоритму виконання операцій OFDM-модуляції:

1. Визначення вимог та характеристик: Першим кроком визначено основні вимоги до алгоритму OFDM-модуляції та ключових характеристик, необхідних для ефективного використання у SDR. Це включило в себе аналіз пропускної здатності, чутливості до помилок, вимог до смуги пропускання та інших технічних параметрів.
2. Розробка та моделювання: Здійснено детальну розробка алгоритму, включаючи вибір методів модуляції та способів їх реалізації. На цьому етапі також виконано моделювання алгоритму для оцінки його ефективності та визначення оптимальних параметрів.
3. Реалізація алгоритму в програмному середовищі: Алгоритм реалізований у вигляді програмного коду, в середовищі Mathcad та написаний на мові C++. Цей крок включав кодування алгоритму, його тестування та відладку.
4. Аналіз результатів та оптимізація: Проведено аналіз отриманих результатів, включаючи оцінку ефективності модуляції, точності передачі даних та впливу на загальну продуктивність системи. Показано ефективність роботи алгоритму через його можливість підлаштовуватись під умови навколишніх завад.

Ключові слова: SDR, ЦСП, радіомоніторинг, інтелектуальна система, OFDM, захисний інтервал, модуляція, алгоритм

Makarenko A., Otrokh S. The use of SDR as sensor nodes of the intelligent system of management of radio emission data collection. The article is devoted to the study of the use of software-controlled radio (SDR) in the context of the growing demand for wireless technologies and radio-electronic devices. It focuses on the problems of oversaturation of the radio spectrum, the need to automate the management of radio systems, security, the use of machine learning and AI, the integration of various systems, as well as economic benefits. The paper examines the SDR as a tool to address these challenges, particularly due to its ability to operate over a wide frequency range and the use of digital signal processing. The role of SDR in radio monitoring and its importance in identifying and eliminating sources of interference are also revealed.

The main attention is paid to the development of the algorithm for performing OFDM-modulation operations in the SDR of intelligent control systems of the radio emission data collection network. The proposed algorithm aims to optimize data transmission, reducing the transmission of redundant bits of information and promoting efficient use of the radio spectrum. The article describes in detail the architecture and functionality of SDR, including an analysis of the impact of OFDM technologies on the efficiency of data transmission within software-controlled systems.

Keywords: SDR, digital signal processor, radiomonitoring, intelligent system, OFDM, guard interval, modulation, algorithm

Introduction. In today's world, the demand for wireless technologies and various radio-electronic devices is growing rapidly. This leads to an increase in the amount of radio emission in the airspace, which becomes a challenge for the stable operation of many communication systems [1].

The relevance of the research topic is as follows:

1. Density of the radio spectrum: Every year, radio electronic devices are becoming more and more common, from simple household devices to complex industrial systems. This leads to oversaturation of the radio spectrum and the need for its efficient use.

2. The need for automation: Manual control and configuration of radio systems is no longer efficient in large networks. Intelligent systems can automatically optimize network parameters, responding to changes in the environment.

3. Ensuring security: The presence of intelligent systems allows you to quickly detect and respond to potential threats, such as unauthorized radio emissions or attempts to interfere with the operation of the network.

4. Machine learning and AI: The development of machine learning and artificial intelligence technologies makes it possible to create increasingly complex and effective algorithms for managing radio networks.

5. Integration of various systems: Intelligent management allows the integration of various monitoring and control systems into a single network, which facilitates management and monitoring.

6. Economic benefit: Effective use of radio spectrum and optimization of network operation can lead to lower costs and increased productivity.

Analysis of recent research and publications. Software-controlled radio (SDR) is a communication system that uses software to implement communication functions that are normally performed by hardware. The software implementation of wireless networks is promising, as it is less expensive and allows you to easily change the perimeters of the system to meet different needs and requirements [1, 2].

It is generally accepted that there is a spectrum availability crisis due to the huge growth of wireless services and the development of new radio communication technologies. In fact, there are many areas of the radio frequency spectrum that are not fully utilized. Cognitive radio (CR) implemented on the basis of SDR is proposed to improve spectrum utilization. The first and most important requirement for the deployment of KR technology is the identification of the main user, which is not an easy task [3, 4].

One of the tasks solved by SDR is radio monitoring [5]. First of all, radio monitoring helps to identify and eliminate sources of interference. It can be anything from an old TV transmitter to faulty mobile phone equipment. Rapid identification and elimination of such problems is important to ensure quality service for users and support the operation of important network infrastructures.

SDR significantly facilitates radio emission data collection due to its unique characteristics [1, 3, 5]:

- SDR can receive and transmit over a wide range of frequencies. This allows you to collect data from various sources of radio emission without the need to change physical equipment.
- SDR uses digital signal processing, which improves the quality of data collection, allowing more accurate detection, decoding and analysis of signals.
- With software customization, the SDR can be quickly adapted to a variety of data collection tasks, from simple monitoring to complex signal analysis.
- The wide frequency range supported by SDR is one of its key advantages. SDR is able to receive and transmit signals in a wide range of frequencies. This means it can collect data from ultra-low frequencies up to gigahertz ranges. This flexibility allows the SDR to be used to monitor a variety of radio signals, which is important for tasks such as intelligence gathering, radio astronomy research, and commercial and scientific research.

However, in the conditions of radio-electronic warfare, the effectiveness of the analysis of radio broadcasts decreases [6], which forces scientists to use new and improve existing methods of improving the operation of radio monitoring systems. One of the solutions to such obstacles is to improve the OFDM modulation methods used in SDR.

The purpose of the article is to develop an algorithm for performing OFDM-modulation SDR operations of an intelligent radio data collection network control system, a distinctive feature of which is the use of only one graph of the inverse Fourier transform, which allows to achieve a two-fold reduction in the transmission of redundant bits of information during their digital processing. This provides an opportunity to reduce the requirements for hardware and software complexity and to use them for application in more complex algorithms for countering radio-electronic warfare.

1. Reference model of SDR construction.

The basic architecture of SDR is shown in Fig. 1 [1]. The main hardware element of this telecommunication system is the DSP.

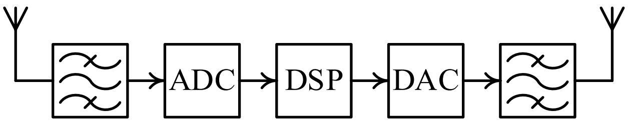

Fig. 1. SDR functional diagram

In fig. 1, to implement the receiver, the input filter must be band-pass, the sampling frequency of the input analog-to-digital converter (ADC) will be determined according to Kotelnikov's theorem. The output digital-to-analog converter must operate at a frequency that is at least twice the signal bandwidth of the main frequency band. The output filter is implemented using a low-pass filter and limits the output signal to the main frequency band.

In many applications, the modulating signal is itself digital. Then the modulation/demodulation is performed on the basis of the ADC and DAC, and the input and output filters can be eliminated and the digital signals are fed to the processor. The DSP implementation on a single chip with an ADC and a DAC turns them into a modem.

This SDR implementation is independent of the chosen modulation type, so any modulation mode for the transmitted signal, analog (AM, FM) or digital (QPSK or QAM), can be implemented using the same hardware and software. This is the main and significant advantage of SDR over telecommunication equipment of previous generations.

In order to accomplish this, digital signal processors or microprocessors must possess a substantial degree of computational prowess. The advancement of the element foundation currently enables the creation of Software-Defined Radio (SDR) systems, which, when combined with software-controlled systems, form the network of the future [7].

We can find many definitions of SDR. The SDR forum, working in cooperation with the Institute of Electrical and Electronics Engineers (IEEE) group P1900.1, has worked to create a definition of SDR that provides consistency and a clear understanding of the technology and its associated benefits [8].

In other words, a software-controlled radio is defined as: "A radio in which some or all of the physical layer functions are defined by software."

SDR defines a set of hardware and software technologies where some or all of the radio's operational functions are implemented through modifiable software or embedded software that affects programmable processing technologies. These devices include user-programmable gate arrays, digital signal processors, general-purpose processors, programmable system-on-chip, or other specialized programmable processors. The use of these technologies allows the creation of new wireless services and the ability to be added to existing radio communication systems without requiring new hardware.

Let's consider in more detail the functional model of SDR presented in Fig. 2 [8, 9].

On the receiver side, this model consists of a radio frequency subsystem that is tuned to a channel or channels of interest from a predetermined frequency band, converts these channels into a base frequency band, and transmits them to the modem subsystem for demodulation and decoding. The modem subsystem transmits the received analog signal or digital data stream that carries information for the network layer or the security processing subsystem, as appropriate.

The reverse process occurs on the transmitting side. In the modem, a digital data stream is coded and a modulated signal is created that carries the information intended for transmission. The signal is then transmitted to the radio frequency subsystem for transmission over a wireless communication channel.

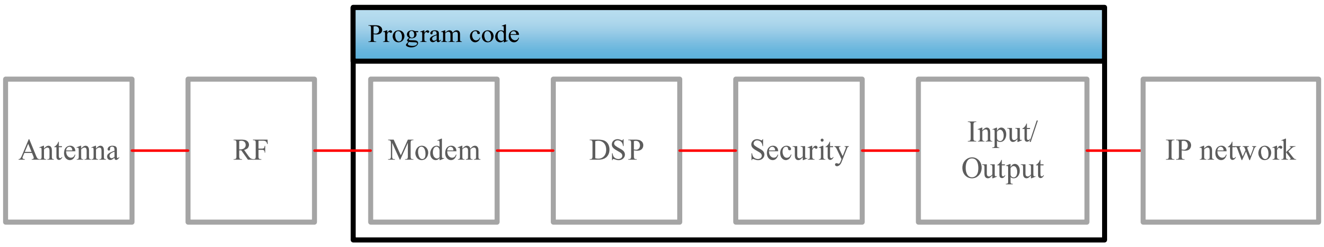

Fig. 2. Reference model of SDR construction

Let's dwell on some nodes in more detail. In the modem, analog-to-digital conversion of the radio frequency subsystem signal and separation of the useful signal from the digitized representation of the output signal is performed. The DSP processor performs channel-level functions of controlling and stabilizing the parameters of elements of the radio frequency subsystem and elements of the antenna -feeder path [1]. If the transmitter encrypts the information flow, then the receiver must be able to decrypt it. Any information that needs to be protected for security purposes is handled in the security subsystem.

2. Cognitive radio as a component of the intellectual system of managing the radio data collection network.

An integral part of the development and formation of the fifth-generation mobile communication networks are intelligent radio communication systems. The MSE report defines a radio communication system with programmable parameters and a cognitive radio system (CRS).

It is a radio transmitter and radio receiver that uses technology that allows you to set operating radio frequency parameters using software [8].

For cognitive radio it is determined that the devices must support several radio access technologies, have the ability to dynamically determine the available technologies, free radio frequency resource and radio monitoring.

The cognitive radio system is organized using (Fig. 2, a):

- control channel;
- databases with information about the surrounding radio space.

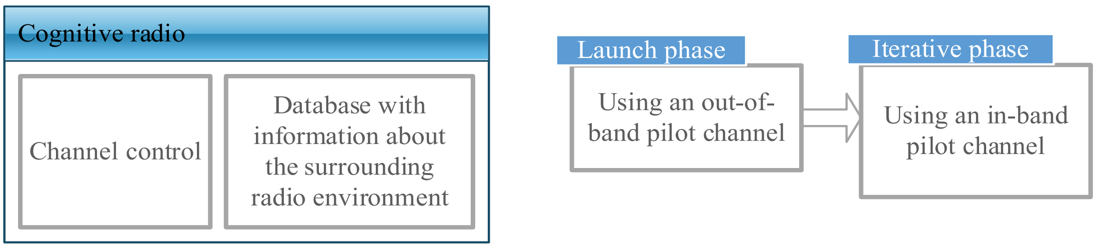

Fig. 2. Organization of the cognitive radio system (a), two main phases in the operation of the radio monitoring terminal (b)

An example of an environment with several emission sources is shown in Fig. 3.

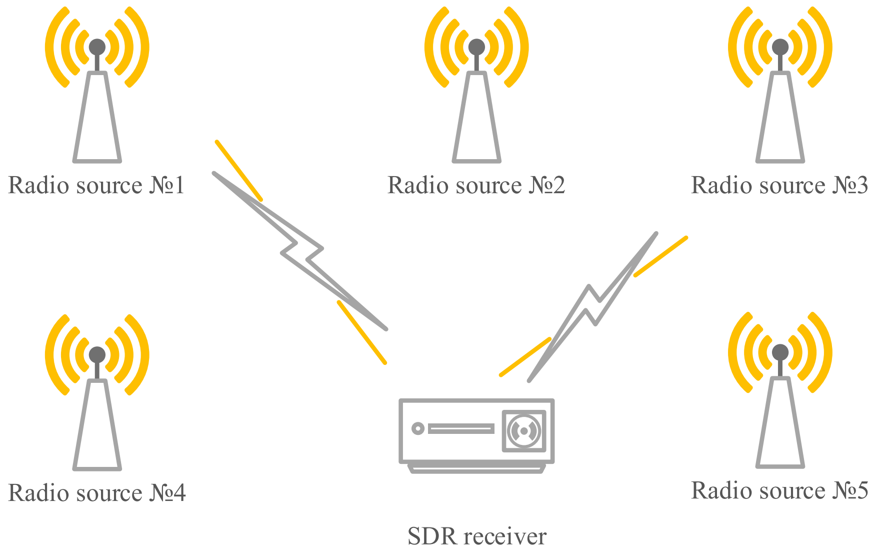

Fig. 3. An environment with several frequency bands

Without any information about the location of multiple radio access technologies within the frequency band reachable from the SDR terminal, it is necessary to scan the entire frequency band in order to know the spectrum occupancy. However, this requires a long time.

In this context, it is necessary to transmit sufficient information in the control channel to the SDR terminal so that it, in turn, can initiate a communication session optimized for time, situation and location. In the control channel, relevant information about frequency bands, radio access technologies, services, and spectrum occupancy status must be transmitted to the terminal location.

In particular, once powered up, the SDR terminal does not know which radio access technology may be most suitable or in which frequency bands the possible radio access technologies operate.

In the operation of the terminal when interacting with the control channel, it is proposed to distinguish two main phases, called the "launch" and "continuation" phases (Fig. 2, b).

The "start-up" phase: after power-up, the terminal determines its geographical location using the positioning system, and later it detects the control signal. After determining and synchronizing with the control signal, the terminal searches for the information transmitted in the control channel, concerning the area of its location, which completes the start-up phase. "Continue" phase: When the terminal is connected to the network, it may be useful to periodically check the information sent from the control signal to quickly detect changes in the environment due to either a change of position or a reconfiguration of the network.

During the operation of the terminal, in the iteration phase, listening is performed not only to the control channel of the cognitive radio system, which is called out-of-band, but also to the control channel of a specific radio access system, which is called in-band.

Another method is to use databases. Artificial intelligence technologies can be effectively applied to the analysis and decision-making stage of cognitive radio systems.

The database contains data about system states and possible actions. The decision maker chooses what action to take. The learning subsystem accumulates knowledge obtained from accumulated information (information about channel occupancy, channel error probability, etc.). The knowledge base works in two modes. Determining the state of the radio broadcast and taking actions to change the system parameters.

LTE System Toolbox is available for researching these technologies in the latest version of Matlab. The process of forming LTE signals can require a large amount of time. LTE System Toolbox makes generating signals much easier. The generated signal can be used in solving a number of tasks, such as checking microwave components on a realistic LTE signal, evaluating the influence of the LTE signal on other wireless systems, as well as testing the correct operation of the LTE receiver.

LabVIEW Communications combines hardware for SDR with comprehensive software for a complete development cycle and enables engineers to prototype fifth-generation communication systems.

VisSim Communications together with the hardware allows you to design SDR receivers.

GNU Radio is a free digital signal processing platform. GNU Radio is a set of programs and libraries that allow you to create arbitrary radio systems, modulation schemes, the form of signals that are received and sent, which are set by software, and the simplest hardware devices are used to capture and generate signals.

3. Development of an algorithm for performing OFDM modulation operations.

In high-speed data transmission systems, the receiver faces challenges related to the development of extra channels induced by intersymbol interference (ISI) when transmitting broadband signals [10]. In broadband transmission systems, the received signal is a combination of several cyclically shifted and weakened replicas of the broadcast signal. Consequently, the delayed copies of the symbols will disrupt the accurate recognition of the current symbols, resulting in intersymbol interference. As the bandwidth of the transmission system rises, the number of symbols that are delayed in time also increases in direct proportion. The equalizer's complexity is significantly heightened due to the need to manage intersymbol interference. OFDM technology is employed to efficiently minimize intersymbol interference and decrease the intricacy of the equalizer.

OFDM technology aims to partition the frequency-sampling channel into many narrow-band sub-channels. Orthogonal narrowband signals are broadcast simultaneously on these subchannels or subcarriers. Due to the occurrence of shallow fading in each of these signals, a straightforward scalar channel correction is adequate.

Each symbol consists of two parts, the first part is a cyclic repetition of the end of the symbol itself, and the second part contains the active symbol as shown in fig. 3 [11]. Full symbol duration $T_{gs}=T_g+T_s$, where T_g is the duration of the protective interval. The length of the guard interval depends on the field of application of the transmission system, but since it reduces the data throughput, the duration of T_g is usually no more than $T_s/4$.

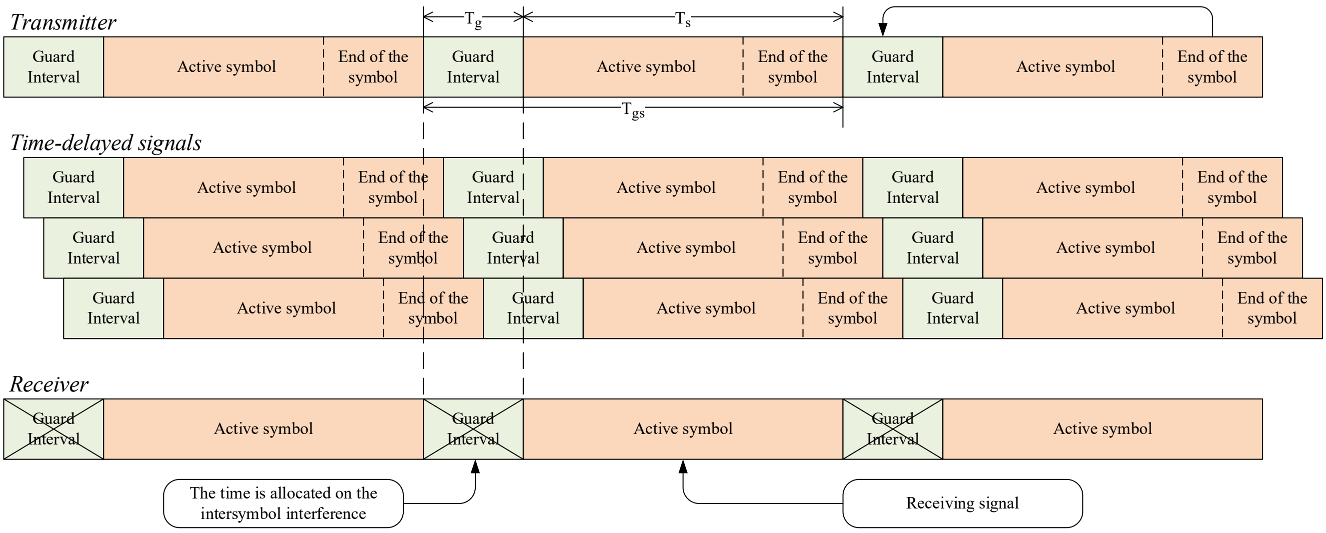

Fig. 3. Time intervals of the main and two time-delayed signals

Also, since the subcarriers are orthogonal, there is essentially no crosstalk between the signals (for a well-designed system), which simplifies the signal detection process.

In fig. 4 shows the structural diagram of the OFDM transmission system [10 - 12].

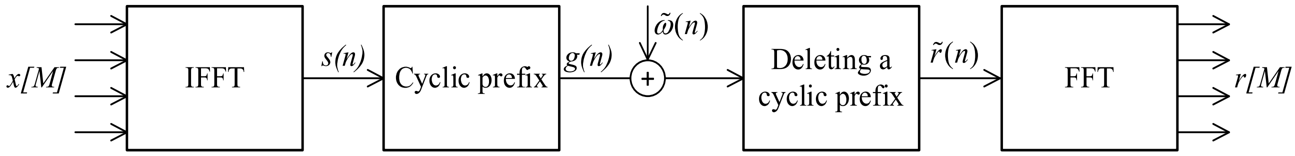

Fig. 4. Simplified structural diagram of the OFDM transmission system

Starting from the transmitter in the left part of the figure, *M* complex symbols *x(m)* are fed to the *M -point* block of the inverse Fast Fourier Transform (FFT). IFFT performs OFDM modulation, where each column of the basic IFFT matrix corresponds to one of the subcarriers of the OFDM symbol. After converting the parallel code into a serial time interval, the signal has the form

$$s(n)=\frac{1}{M}\sum_{m=0}^{M-1}x(m)e^{j2\pi\frac{nm}{M}} \tag{1}$$

for $n = 0...M-1$. As you can see, this is only the sum of complex exponentials, i.e. sinusoidal and cosinusoidal functions [10, 12].

After adding a cyclic prefix, the signal is transmitted over a communication channel with time-varying parameters and frequency-selective fading caused by multipath propagation of radio waves with an impulse response *g(n),* which is assumed to be no greater than the cyclic prefix. In the process of passing a signal through a communication channel, the signal is affected by white normally distributed Gaussian noise $\tilde{\omega}(n)$ [12]:

$$\tilde{r}(n)=s(n)+s(n+t)+\tilde{\omega}(n). \tag{2}$$

In the receiver, under the condition of synchronization and removal of the cyclic prefix, the received time interval $\tilde{r}(n)$ contains an overlay of delayed copies of the transmitted OFDM symbol.

In a channel with time-varying parameters and frequency-selective fading caused by multipath propagation of radio waves, a cyclic prefix is required to maintain orthogonality between subcarriers. The requirement for orthogonality is that all delayed copies of a transmitted OFDM symbol overlap in an observation interval of length *M* (or *T* in continuous time). This is achieved by adding the cyclic prefix. Orthogonality is required for the OFDM to fully separate the different components of the OFDM symbol signal at the receiver. Without the cyclic prefix, replacing it with an empty guard interval, the delayed signals would partially fall outside the observation interval, and the orthogonality between the subcarriers would be lost.

Based on the above in fig. 5, a, presents the algorithm for performing OFDM modulation operations. The first block in the algorithm is responsible for entering input data and determining the characteristics of the operands that will be used in further calculations.

In the next block, the operations of forming the data flow into frames are performed. Block number 3 determines the number of symbols per frame. In blocks 4 and 5, QAM-modulation (or other type of modulation depending on the need) and OFDM-modulation using OSHPF are performed. The OFDM frame formation check is performed in the 6th cyclic block. The next block is designed to define, form and add a guard interval to the OFDM frame. The operation of amplifying the amplitude value of the frame according to the level of the communication channel is performed in the 8th block. The last block performs the function of preliminary preparation for the formation of the output signal, the possibility of outputting data and connecting a DAC.

When using the developed algorithm for performing OFDM-modulation operations in the Mathcad software environment, a graph of the error rate for various types of modulations was obtained. In block 4, the modulation algorithm is successively replaced with the one presented below (Fig. 5, b).

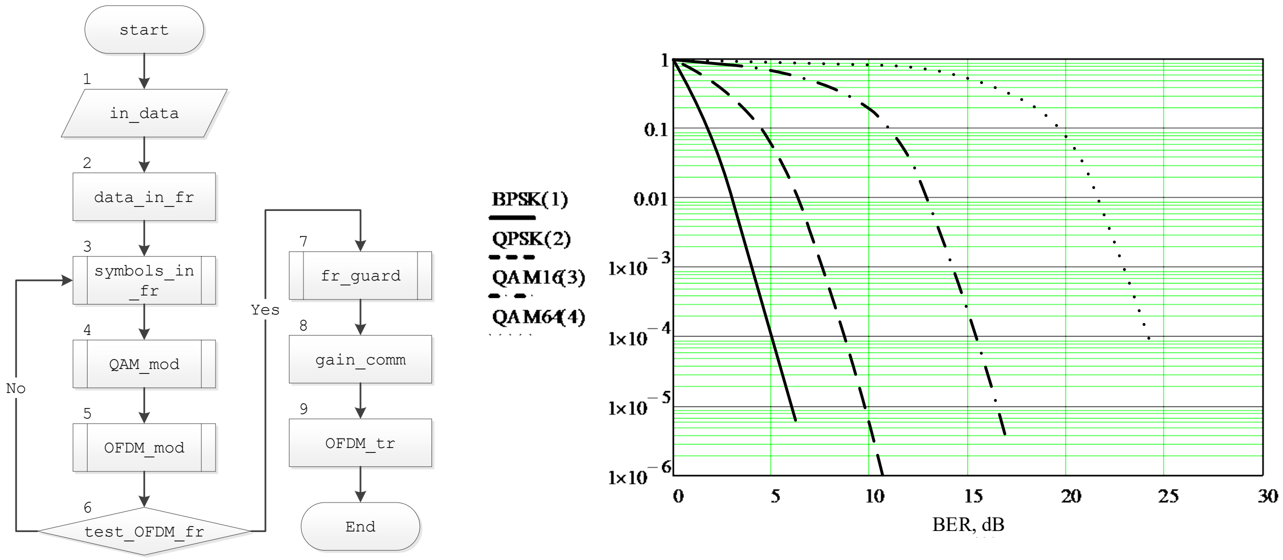

Fig. 5. Algorithm for performing OFDM modulation operations (a), graph of the error rate for different types of modulations (b)

Accordingly, for each type of modulation, it is necessary to provide a signal-to-interference ratio level that is not higher than some acceptable level necessary for the transmission of bits of information with errors. In modern software-controlled systems, a maximum error rate of no more than 10^{-6} has been determined. Analyzing the graph, we will conclude, however, that when transmitting data at the maximum possible speeds that an OFDM-SDR transceiver can provide, it is necessary to use QAM modulation, ensuring a low level of interference. If this condition cannot be met, switch to lower modulation levels, up to BPSK, reducing the speed of data exchange.

Conclusions and proposals.

The work developed an algorithm for performing OFDM modulation operations in SDR of intelligent control systems of the radio emission data collection network. The proposed algorithm aims to optimize data transmission, reducing the transmission of redundant bits of information and promoting efficient use of the radio spectrum. The article describes in detail the architecture and functionality of SDR, including an analysis of the impact of OFDM technologies on the efficiency of data transmission within software-controlled systems.

Based on the obtained research results, the following recommendations can be given in the article regarding the use of the obtained results:

1. Implementation of the developed OFDM-modulation algorithm in modern radio systems: In view of the increased efficiency and optimization of the use of the radio spectrum, it is recommended to implement the developed algorithm in software-controlled radio systems, especially in those where it is important to reduce redundant bits of information during transmission.

2. Optimizing the selection of the modulation type depending on the operating conditions: The selection of the modulation type should be based on the analysis of the error rate for different modulations to ensure the best balance between the bandwidth and the reliability of data transmission in specific operating conditions.

3. Application to increase the efficiency of radio monitoring: Since the algorithm allows more accurate detection and analysis of radio signals, it should be used to increase the efficiency of radio monitoring, especially in areas where accurate analysis of radio emissions is important.

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