Virtual laboratory work to the study of modulation types of radio signals

Yevgeniya Daineko[1,†], Dmitry Gubsky[1,†], Aigul Kulakayeva[1,†], Altay Aitmagambetov[1,†] and Bagdat Kozhakhmetova[1,*,†]

[1] International Information Technology University, 34/1 Manas St., Almaty, 050040, Kazakhstan

Abstract

This paper presents computer models of modulators for studying the amplitude and frequency modulation of radio signals. The developed models can be integrated with a spectrum analyzer, which is part of a virtual laboratory for visualization and analysis of modulated radio signals in the frequency domain. The process of creating a virtual laboratory is described in detail in this paper. In addition, the results of a survey of its implementation in the educational process are presented, which showed student satisfaction when working with the laboratory. The developed models, as well as the entire virtual laboratory, can be effectively used both in the traditional training format and in distance learning. A set of software tools, including computer models of radio signal modulators, a spectrum analyzer and virtual laboratory work, was created using the MS Visual Studio environment in the C++ programming language.

Keywords

microwave devices, modulation, computer simulation, distance education, virtual laboratories

1. Introduction

Today, in the field of educational technologies, one of the most popular areas among researchers around the world is the creation of virtual laboratories (VL) for the study of various disciplines. VL allows students to conduct experiments and work with models of complex systems in a safe and controlled environment. They provide access to equipment and resources that may not be available in traditional laboratories due to high cost or limited quantity [1]. The interactivity and multimedia capabilities of virtual laboratories make the learning process more exciting and motivating, which contributes to a deeper assimilation of knowledge and the development of practical skills among students [2].

When preparing students of technical fields, laboratory work plays a key role in the learning process, since it provides practical application of theoretical knowledge gained during lectures and seminars [3]. In the process of completing laboratory tasks, students are faced with real tasks and equipment, which contributes to an in-depth understanding of the material and the development of skills for solving practical problems. In the context of globalization and the spread of online education, the introduction of virtual laboratory work is an integral tool in the training of highly qualified specialists, contributing to a better and modern education of students of technical fields [4].

Virtual laboratories and environments have become valuable tools for studying radio signals and improving the level of radio engineering education [5]-[12]. For example, in [5-7], the authors

DTESI 2024: 9th International Conference on Digital Technologies in Education, Science and Industry, October 16–17, 2024, Almaty, Kazakhstan

* Corresponding author.
† These authors contributed equally.
y.daineko@iitu.edu.kz (Y. Daineko); d.gubsky@iitu.edu.kz (D. Gubsky); a.kulakayeva@iitu.edu.kz (A. Kulakayeva); a.aitmagambetov@iitu.edu.kz (A. Aitmagambetov); b.kozhakhmetova@iitu.edu.kz (B. Kozhakhmetova)
0000-0001-6581-2622 (Y. Daineko); 0000-0001-6651-5953 (D. Gubsky); 0000-0002-0143-085X (A. Kulakayeva); 0000-0002-7808-5273 (A. Aitmagambetov); 0000-0002-9566-3629 (B. Kozhakhmetova)

present an interactive platform for modeling spectrum analyzers and signal modulators, allowing students to visualize complex radio processes.

In [8-10], a method of modulation and demodulation of signals based on LabVIEW is presented. The results are displayed in both the time and the frequency domain. The modulation parameters are set by the user, and the interface itself is simple and easy to use.

The processes of modulation and demodulation of amplitude-modulated (AM) generated using NI USRP-2920 and received using RTL-SDR using the Matlab/Simulink program are presented by researchers in [11]. This paper clearly presents the main stages of signal reception and processing, mathematical models, as well as signal modulation and demodulation schemes, which is necessary for use in the educational process. The study of a more complex OFDM signal using SDR is presented in [12]. In this paper, the SDR development is based on the integration of Matlab/Simulink and the Raspberry PI 3 B+ platform. This, in turn, allows you to study digital communication systems, understand the principles of digital signal processing, FPGA operation, and simulate the OFDM system. The results of the work are presented on spectral diagrams and correspond to the transmitted and received signal.

An analysis of existing studies devoted to the creation of virtual laboratory complexes for studying the parameters of radio signals has convincingly demonstrated their high efficiency. Many of these developments have already found their application in university educational program and are actively used by students. Virtual laboratory work not only increases interest in further study of the discipline, but also stimulates the development of creative and critical thinking among students, allowing them to better understand and apply theoretical knowledge in practice. In addition, such complexes open up new opportunities for individualization of learning, which is especially important in the context of the modern educational process. The purpose of this work is to create a computer model of modulators for studying various types of radio signal modulations

2. Problem statement

To develop modulator models, previously developed requirements [14] for models of the studied devices and virtual measuring devices must be taken into account. Compliance with these requirements will ensure the integration of new devices into a virtual laboratory, which will effectively study the spectra of harmonic signals with amplitude and frequency modulation. As a result, the created models will not only meet the necessary technical standards, but also contribute to improving the accuracy and effectiveness of training, providing students with high-quality tools for practical mastering of complex radio engineering concepts. At the same time, the interface of the computer model should be intuitive and functional, giving the user the opportunity to change the characteristics of both the carrier and the modulating signal, as well as choose the types of modulation and their parameters from the available options.

Such a model should be able to integrate with a previously created spectrum analyzer model [13]. To do this, the modulator model must convert the input signals into a modulated signal in accordance with the user's selected mode, convert this signal into a frequency representation using the Fourier transform and generate an array of data to transmit the spectrum analyzer model. This array should include the frequency and amplitude values of the spectral components of the modulated output signal for subsequent processing and visualization.

To demonstrate the operation of the created device models in combination with the already existing spectrum analyzer model, a laboratory work has been created, which has already been tested and implemented into the educational process.

3. Modeling of a spectrum analyzer

When creating a laboratory work on the study of radio signal modulation, the developed model of the spectrum analyzer will be used [13]. Its development used a general approach [14], which allowed it to be included in the virtual laboratory [1].

According to this concept, the measuring device must receive an input signal from the device under study and process it in accordance with the settings and the selected spectrum display mode. In this case, the input signal must be represented as an array of data (frequency and amplitude of the spectrum component), the number of elements in the array depends on the number of spectral components in the analyzed signal.

The most frequently used functions are implemented in the computer model of the spectrum analyzer. Such as: setting the viewing band and displaying the frequencies of the studied signal, setting the amplitude parameters and the measuring line, as well as working with markers. These functions are quite sufficient to carry out most of the necessary measurements and to obtain the user's primary skills in working with the measuring device. The user selects the appropriate functions by pressing the buttons on the device with a computer mouse and/or selecting the desired items in the on-screen menu.

The user also has the ability to enter the necessary data, for example, setting the center frequency, viewing band, etc. The interface of the spectrum analyzer model is presented in [5], where you can see its full realism and visual compliance with the real device.

The operation of the spectrum analyzer model is reduced to performing certain actions when pressing the appropriate keys. These actions can be divided into two types: with or without redrawing the characteristics of the connected device on the device screen. If redrawing of the characteristic is not required, for example, when working with markers or a measuring line, then the actions performed do not require repeated output of the input signal spectrum. In this case, all the functionality is implemented by internal methods, without accessing the connected source of the studied radio signal. For example, when the user selects the maximum value search function (PEAK SEARCH menu), a method is called that searches for the maximum value in a previously created and saved array, where the index is the frequency. After finding this index, the corresponding method is called, which "draws" the marker with the specified coordinates and the values displayed on the screen. All other internal methods of the device are implemented using a similar algorithm.

If it is necessary to redraw the displayed spectrum of the studied radio signal (for example, when the user changes the viewing band), a previously obtained data set is accessed, which is an array of frequencies and amplitudes of the spectral components of the studied radio signal. After processing this data set, the displayed spectrum is updated in accordance with the user-defined settings of the measuring device. For example, when changing the viewing band, some spectral components that do not fall into the new viewing band will not be displayed on the screen. A complete spectrum update is carried out only when the input signal changes or upon request from the connected device under study.

4. Creating a modulator model for studying various types of radio signal modulation

Let's consider the creation of modulator models to study various types and parameters of radio signal modulation. In communication technology, amplitude and frequency modulation, which is a special case of phase modulation, as well as their modifications, are the most common and widely used. Therefore, it is necessary to create a device model that will allow the user to change the characteristics of the message and the carrier oscillation, as well as study the spectral characteristics of the signals using a spectrum analyzer model.

The model of the modulator under study can be conventionally represented as a "black box" [5], which includes the modulator itself (in the computer model there is a choice of the type of modulation: amplitude or frequency) and an output signal processor (Figure 1).

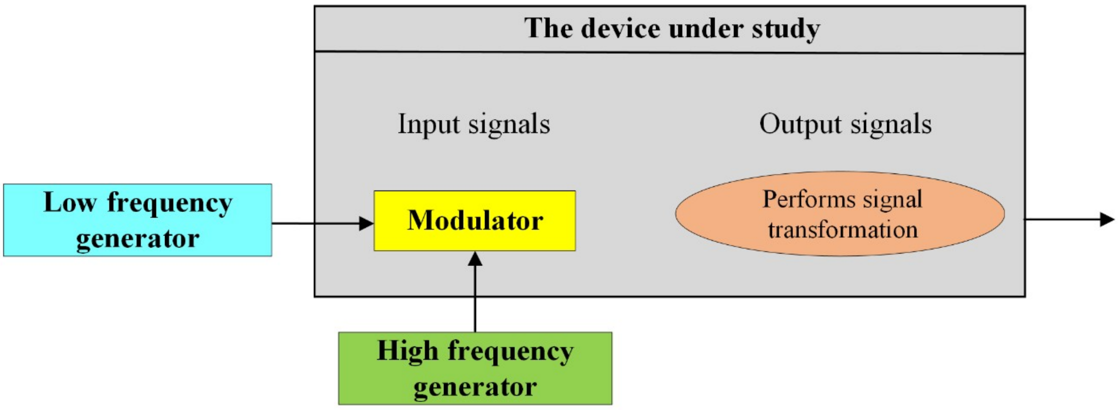

Figure 1: Block diagram of the model of the device under study.

The processor converts the output signal of the modulator into the form necessary for transmission to the spectrum analyzer model. Two harmonic signals are applied to the input of the modulator: a carrier frequency signal (for example, from a high frequency generator) and a modulating low frequency signal (for example, from a low frequency generator). The user should be able to change the frequency and amplitude of these signals. Both signals are then converted by the modulator according to the user-selected modulation mode (amplitude or frequency).

After that, additional processing of the modulated signal is carried out in the model of the device under study, during which, in accordance with the developed concept, the Fourier transform is performed and the spectral representation of the output signal is calculated. Next, all the necessary data is generated for transmission to the spectrum analyzer model for further processing and display on the screen. Let's look at this process in more detail.

Suppose that a harmonic oscillation is received at the input of the modulator, which is a carrier high-frequency oscillation:

$$U(t)=U_0\cos(\omega_0 t+\varphi_0), \tag{1}$$

where U_0 – amplitude, $\omega_0 = 2\pi f_0$, and f_0 – carrier frequency, φ_0 – initial phase.

And the second signal is a modulating signal (message), which for simplicity we represent as harmonic:

$$U_c(t)=U_{c0}\cos(\omega_c t+\varphi_c), \tag{2}$$

where U_{c0} – amplitude, $\omega_c = 2\pi f_c$, f_c – signal frequency, φ_c – initial phase.

Then, depending on the selected modulation type mode, you can determine the output signal.

4.1. Amplitude modulation (AM)

Let us consider the case of amplitude modulation, which is the simplest for analysis. As a modulating signal, we use harmonic oscillation (2). This type is called tone modulation. In this case, the angular frequency ω_0, ω_c, and the initial phase φ_0 of the carrier oscillation remain unchanged, and with the help of modulating oscillation $U_c(t)$ the amplitude of the carrier oscillation changes $U(t)$. In this case, for the received amplitude-modulated signal, we can write:

$$U_{am}(t)=(U_0+k_a U_c(t))\cos(\square_c t+\square_c), \quad (3)$$

where k_a – amplitude modulation coefficient, reflecting the degree of influence of the modulating signal on the magnitude of the change in the amplitude of the carrier wave; $U_c(t)$ – time-dependent function corresponding to the transmitted message (modulating signal).

To simplify the analysis, the initial phases of oscillations (1-2) can be set equal to zero. This will not affect the conclusions and reasoning. Then, substituting (2) into (3) and performing the necessary transformations, we can write the resulting signal with amplitude modulation as the sum of oscillations:

$$U_{am}(t)=U_0\cos(\square_0 t+\square_0)+U_0\frac{k_a}{2}\cos(\square_0+\square_c)t+U_0\frac{k_a}{2}\cos(\square_0-\square_c)t, \quad (4)$$

where $k_a = U_c/U_0$ – amplitude modulation coefficient characterizing its depth.

In order to avoid distortion of information, it is accepted that $0 \le k_a \le 1$. AM-oscillation consists of three harmonic oscillations with close frequencies. The width of its spectrum is equal to twice the modulation frequency ω_c.

Thus, in order to obtain the resulting modulated signal in the model in the spectral representation, you can form it based on the analytical representation, or you can perform the Fourier transform. According to the requirements for the output signal of our device model, we need to form an array of data to transfer the spectrum analyzer model for further processing. The transmitted array is presented in [5].

4.2. Frequency modulation (FM)

Frequency-modulated oscillation is an oscillation, the frequency of which changes in proportion to the modulating signal (2) with a constant oscillation amplitude. In such a way:

$$(t)=\square_0+\Delta*U_c(t), \quad (5)$$

where the quantity $\Delta\omega$ – is called the frequency deviation, $U_c(t)$ – modeling signal (2).

Therefore, the resulting FM signal can be written as:

$$U_{fm}(t)=U_0\cos(\square_0+\Delta*U_c(t)), \quad (6)$$

The parameters characterizing the FM are the frequency deviation $\Delta\omega$ and $\beta = \Delta\omega/\beta 0$ – the frequency modulation index, which is the ratio of the frequency deviation to the frequency of the modulating signal. In the case of an FM signal obtained as a result of modulation with a single-tone modulating signal, one can write a complex representation of Ufm(t). Using the expansion in a Fourier series, we get:

$$U_{fm}(t)=U_0\sum_{k=-\infty}^{\infty} J_k(\beta)\cos(\square_0+k\square_C)t), \quad (7)$$

Here, for convenience, the initial phases of oscillations (1-2) can be set equal to zero. It can be seen that the spectrum contains an infinite number of side harmonics, pairwise symmetrical with respect to the carrier frequency ω_0. The amplitudes of all components, including the carrier, are proportional to the values of the Bessel functions from the value of the frequency modulation index. It should be noted that the Bessel functions are slowly decaying, which in the real case limits the spectral representation of the signal to 5-10 components. It is also necessary to consider that, at certain values of β the Bessel functions vanish, which makes it possible to obtain the minimum amplitude for the component of the spectrum with the carrier frequency.

Thus, in order to obtain the resulting modulated signal in the spectral representation in the frequency modulator model, it is necessary to calculate the Fourier transform. As a result, we obtain the values of the spectral components of the studied signal and can form an array of data to transmit them to the spectrum analyzer model for further processing 5).

Thus, we have obtained arrays that should form a model of the studied signal modulator, depending on the type of modulation, as well as on the frequency and amplitude of the carrier oscillation and the modulating signal (message). In addition, with frequency modulation, the user should be able to change the frequency deviation. All this is implemented in the user interface of the model, which is shown in [5].

5. Creation of a laboratory work and its approbation

The created device model for studying various types of modulation was integrated into a virtual laboratory [1], which significantly expanded its practical application. Thanks to this integration, the model was connected to a virtual model of the HMS 3000 spectrum analyzer developed by Rohde&Schwarz. This made it possible not only to use the model for educational purposes, but also to create a new laboratory work, including the study of the spectral characteristics of modulated signals in real conditions.

Thus, the user can choose different types of modulation (amplitude or frequency), set the frequency and amplitude of the carrier signal and message (modulating low-frequency signal) [5], as well as measure the spectral representation of the radio signal on the screen of the spectrum analyzer model [5]. By changing these parameters, users can study their effect on the radio signal spectrum and understand the dependence of spectral characteristics on various settings. For example, by selecting frequency modulation and changing the amount of frequency deviation, the user can observe on the screen of the spectrum analyzer model a change in the amplitude of the spectral component of the signal at the carrier frequency.

To assess the adequacy of the operation of the spectrum analyzer and modulator models, a detailed comparison of the results obtained using virtual laboratory work with the data recorded on real equipment was carried out. During testing, it was found that the frequency representation of the signals in both cases is completely the same, which confirms the correctness of the virtual models in terms of frequency analysis. However, when comparing the amplitudes of the spectral components of the signal, small discrepancies were found. These differences did not exceed 3%, which is a slight deviation. Such discrepancies can be explained by losses in real transmission lines that were not taken into account in the virtual models. These losses are inevitable in physical systems, but their absence in virtual models suggests that simulations are focused on idealized conditions. In real conditions, additional factors may occur that affect the amplitude of the signal. Thus, it can be argued that the comparison confirmed the high degree of accuracy and reliability of the developed virtual models.

Also, the created virtual laboratory work was tested in the educational process, including its implementation in a remote format. Most of the students noted that the virtual model of the spectrum analyzer almost completely corresponds to the real device, both in terms of the user interface and in terms of operation. The survey showed that students like to start getting to know devices through their virtual models. They consider working with virtual devices to be easy and intuitive, and the absence of fear of "breaking a real device" allows them to focus on understanding physical patterns. The experience gained in carrying out measurements on virtual equipment subsequently facilitates the transition to working with real devices. The interviewed students believe that this laboratory work helped them understand and master the principles of studying the spectrum of radio signals and making measurements using spectrum analyzers.

The structure of the survey consisted of 32 questions with answers in the form of a five-point scale, where 1 is minimum and 5 is maximum. Also, 3 questions were to test the honesty of the respondents with the answer options «Yes» and «No» and 2 open questions to identify sections that were not reflected in the general questions according to the user. Fig. 2 shows the results of student responses.

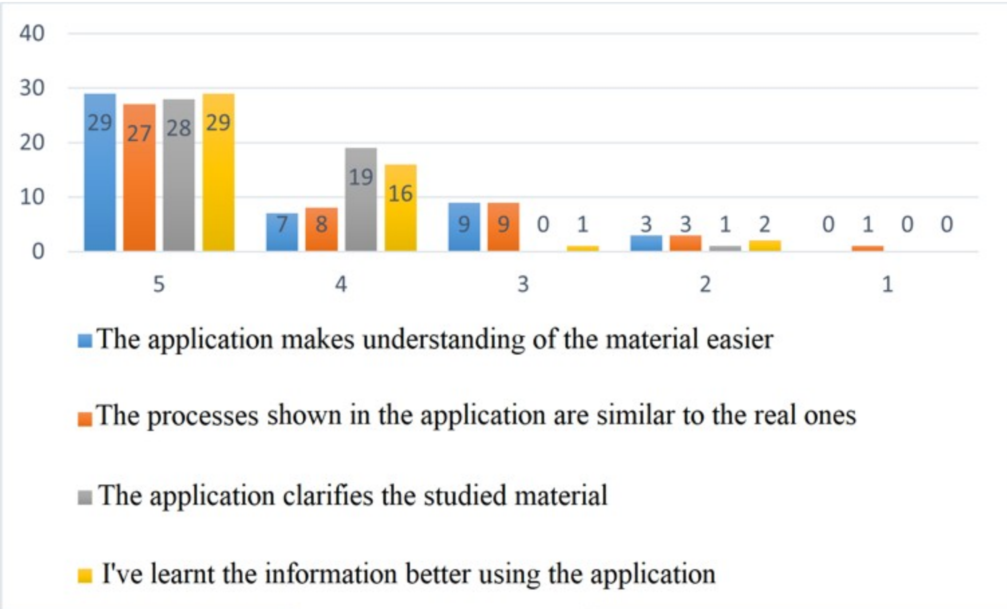

Figure 2: The results of the questionnaire of IITU students.

The diagram shows the positive response of the students to the use of the created web platform in the educational process. According to the users, the created mobile platform facilitates and simplifies the perception of the studied material. Students noted that they were involved in the learning process due to the visual demonstration and virtualization of the process of performing laboratory work, the possibility of visual control of the experiment, and the realism of the appearance of measuring instruments and devices.

Also, the students consider working with virtual devices easy and intuitive. Also, the fact that they are not afraid of “breaking the device” allows them to concentrate on understanding physical laws. In addition, the students note the usefulness of the application and that it meets the expectations of the majority. The experience gained in carrying out measurements on virtual equipment allows them to easily switch to work on real equipment in the future. The interviewed students believe that this laboratory work allowed them to understand and master the principles of studying the spectrum of radio signals and making measurements using spectrum analyzers.

6. Conclusion

During the research, a computer model was developed to study the modulation of radio signals using the HMS 3000 spectrum analyzer from Rohde&Schwarz. This virtual laboratory work has been successfully integrated into the educational process, including the distance learning format. During the survey, students noted the high similarity of the virtual model with the real device, which is confirmed by the results of the survey. More than 90% of students scored "5" or "4" according to criteria such as simplification of understanding of the material, realism of the processes shown in the application, and improvement of information assimilation. These data confirm the effectiveness of the virtual laboratory in the educational process and its significant benefits for students.

Thus, the virtual laboratory allowed students to easily master the material, get rid of the fear of working with real equipment and improve their understanding of physical patterns.

Also, a detailed comparison of the results obtained using virtual laboratory work with data recorded on real equipment confirmed the accuracy of virtual models, with minor deviations associated with the lack of accounting for losses in real transmission lines.

Acknowledgements

This research was funded by the Strategic Academic Leadership Program of the Southern Federal University ("Priority 2030").

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] Gubsky D.S., Kleschenkov A.B. and Mamay I.V. “Virtual laboratory for microwave measurements”. Computer Applications in Engineering Education, 27, No.6, (2019): 1496–1505.

[2] C. N. Triejunita, A. Putri Y. Rosmansyah, "A Systematic Literature Review on Virtual Laboratory for Learning," 2021 International Conference on Data and Software Engineering (ICoDSE), Bandung, Indonesia, 2021, pp. 1-6, doi: 10.1109/ICoDSE53690.2021.9648451

[3] Estriegana, R., Medina-Merodio, J. A., & Barchino, R. Student acceptance of virtual laboratory and practical work: An extension of the technology acceptance model. Computers & Education, 135, (2019): 1-14.

[4] D. Galvez, L. Delgado, C. Caceres and L. Villarroel, "Virtual Laboratory, a Learning Resource for Distance Education," 2022 IEEE 28th International Conference on Engineering, Technology and Innovation (ICE/ITMC) & 31st International Association For Management of Technology (IAMOT) Joint Conference, Nancy, France, 2022, pp. 1-6, doi: 10.1109/ICE/ITMC-IAMOT55089.2022.10033177.

[5] D. S. Gubsky, Y. A. Daineko, A. B. Kleschenkov, M. T. Ipalakova and A. Z. Aitmagambetov, "Virtual Laboratory Work for Studying the Spectrum of Radio Signals," 2022 International Conference on Actual Problems of Electron Devices Engineering (APEDE), Saratov, Russian Federation, 2022, pp. 130-133, doi: 10.1109/APEDE53724.2022.9912973.

[6] Daineko, Y.A., Kozhakhmetova, B.A., Kulakayeva, A., Tsoy, D., Aitmagambetov, A.Z., Gubsky, D.S., Ipalakova, M.T., & Seitnur, A. Development of Virtual Laboratory Work on the Base of Unity Game Engine for the Study of Radio Engineering Disciplines. International Conference on Augmented and Virtual Reality, 2021.

[7] Daineko Y., Tsoy D., Ipalakova M., Kozhakhmetova B., Aitmagambetov A., Kulakayeva, A. Development of an Interactive Mobile Platform for Studying Radio Engineering Disciplines Using Augmented Reality Technology. International Journal of Interactive Mobile Technologies, 16(19), (2022).

[8] Hengkietisak S., Tipyakanont S., Tangsiriworakul C., Manop C., Senavongse W. Laboratory digital signal analysis with virtual spectrum analyzer. IEEE International Conference on Industrial Technology, 2005, pp. 857-860, doi: 10.1109/ICIT.2005.1600755.

[9] Kandasamy N., Telagam N., SeshagiriRaoV. R., Arulananth T. Simulation of Analog Modulation and Demodulation Techniques in Virtual Instrumentation and Remote Lab. Int. J. Online Eng., 13, (2017):140-147, doi:10.3991/IJOE.V13I10.7575.

[10] Uluışık Ç., Sevgi, L. A LabVIEW-Based Analog Modulation Tool for Virtual and Real Experimentation. IEEE Antennas and Propagation Magazine, 54, (2012): 246-254. doi:10.1109/MAP.2012.6387838.

[11] Crivova A. Research on the use of RTL-SDR and MATLAB environment on the example of transmission and reception of AM-DSB-TC. Kronos 7.8 (70) (2022): 50-54.

[12] Hadi Zaidoon Y., Manal J. Al-Kindi. Design and Implementation of Software Defined Radio System for OFDM Communications. International Journal of Mechanical Engineering 7.2 (2022).

[13] D. S. Gubsky, Ye. A. Daineko, M. T. Ipalakova, A. B. Kleschenkov, A. Z. Aitmagambetov, S. A. Vyatkina. Spectrum Analyzer Model for a Virtual Laboratory. Photonics & Electromagnetics Research Symposium (PIERS), 2021, Hangzhou, China, 22 November, 373–376

[14] D.S. Gubsky, V.V. Zemlyakov, D.V. Lonkina "Virtual laboratory for microwave engineers education", Progress in Electromagnetics Research Symposium (PIERS), 2016, 3451 – 3454.