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Received 30.03.2026
Revised 14.05.2026
Accepted 22.05.2026

https://doi.org/10.53360/2788-7995-2026-2(22)-17

IRSTI: 50.53.17

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MODELING AND ANALYSIS OF INTERFERENCE IN WIRELESS DATA TRANSMISSION SYSTEMS

Abstract: *This paper presents a hardware and software platform for modeling and analyzing interference in wireless data transmission systems aimed at studying the reliability and stability of modern wireless communication networks. The relevance of the research is driven by the rapid growth of Internet of Things devices, the active deployment of Wi-Fi and 5G technologies, and the increasing requirements for communication quality and reliability under external electromagnetic interference conditions. The main* *objective of the study is to develop a universal tool for generating, simulating, and analyzing different types of interference in wireless communication channels with real-time visualization capabilities.*

The hardware architecture includes a transmitter, receiver, and interference generator implemented on ESP32 microcontrollers. Software for controlling device parameters and simulation scenarios was developed in the C++ programming language using the Arduino IDE environment. Data exchange between system modules is organized through the WebSocket protocol within a unified Wi-Fi network, enabling synchronous real-time transmission and processing of signals. The paper describes the electrical schematics of the developed devices, the interaction architecture of the modules, and the operating algorithms of the system components.

The proposed platform makes it possible to simulate electromagnetic, noise, and adjacent-channel interference, analyze the influence of amplitude modulation on data transmission quality, and evaluate the stability of wireless communication channels. Experimental testing confirmed the effectiveness of the developed model and the operational reliability of the system. Due to its flexible architecture, the platform can be adapted for research on Wi-Fi, Bluetooth, and ZigBee technologies and can be effectively used in scientific and educational laboratories for developing and testing new interference mitigation methods in wireless networks.

Key words: *wireless network, interference, modeling, ESP32, Wi-Fi, amplitude modulation, WebSocket, hardware-software platform.Key words: modulation, interference, wireless network, software, ESP32, simulation.*

Introduction

Wireless technologies are of great importance in the modern world for ensuring communication between people, devices and systems. The relevance of wireless communications is explained by its wide range of applications, convenience, flexibility, cost-effectiveness and ability to support modern technologies and innovations. With the rapid development of technology and the increase in the number of connected devices the role of wireless communications will only increase [1,2], contributing to further progress and improving the quality of life of people.

The reliability of wireless networks impacts the efficiency and security of systems ranging from consumer IoT to mission-critical industrial and medical applications. With the increase in the number of devices and the volume of transmitted data, the problem of interference in wireless channels becomes relevant [3,4]. Interference can lead to failures in data transmission, deterioration in communication quality, and even complete system failure. The introduction of new anti-interference techniques and modulation technologies opens up opportunities to improve the reliability and performance of wireless networks. In addition, due to the rapid transition to 5G and the creation of new next-generation networks, the study of interference and methods for eliminating it has become strategically important [5-7]. Scientists and engineers will be able to better understand and control wireless communication components using hardware for generating and modulating interference, and software for analyzing and modeling it. There is a sufficient range of different simulators and platforms on the market that are focused on modeling radio channels in wireless networks. For academic purposes and scientific research, open and flexible platforms such as MatLab, CaST, CupCarbon, NS-3, OMNeT++ are used. The authors conducted research related to the analysis of problems in modern wireless networks, the impact of interference in optical wireless networks based on simulation modeling [8, 9]. However, existing problems that hinder the widespread use of emulators are highlighted: high cost, the need to maintain and update systems, and complex technology [10].

This creates a need to develop more accessible and user-friendly solutions that reduce costs, simplify the operation process and make the use of simulators more intuitive for users.

This work set the task of implementing a hardware platform for generating, modulating and analyzing interference in wireless data transmission channels, as well as developing software for modeling and analyzing this interference.

The aim of the research is to deepen the understanding of the physical processes occurring in wireless networks as a result of influence of interference in order to identify effective approaches to control and minimize them.

Materials and methods

The operating principle of wireless communications is based on the transmission of data via electromagnetic waves through airspace. This process can be broken down into several key steps. In the first stage, the data to be transmitted is converted into a form suitable for transmission over a wireless network. This is done through modulation, a process in which information, such as a digital signal, is converted into an analog signal with a specific frequency and amplitude.

Devices that model, amplify, and transmit information over the air are called transmitters. A transmitter converts an analog signal into electromagnetic waves and transmits them to a receiving device. The next step is receiving the signal and converting it. The receiving device, using an antenna, captures the signal and converts it into the original data. Thus, the operating principle of wireless communication includes modulation, transmission, propagation, reception, and demodulation of the signal.

It is important to use modern signal management and filtering techniques to minimize the impact of interference on the signal [11]. The effective use of adaptive filters and noise reduction technologies can significantly improve the quality of communications. Adaptive filters are able to dynamically change their parameters depending on environmental conditions and the level of interference, which makes them ideal for use in mobile communications and radio broadcasting. In addition, the use of various types of coding, such as forward error correction coding, can significantly reduce the impact of errors caused by interference by restoring the original data even if it is partially lost during transmission [12]. Also important is the use of channel diversification, when several frequencies or channels are used simultaneously to transmit the same information, which significantly reduces the risk of complete data loss due to interference on one of the channels [13, 14]. Such methods not only ensure the reliability and quality of data transmission in conditions of high interference, but also increase the stability of communication. A promising direction in wireless communication systems is the implementation of intelligent control systems of spectrum capable of analyzing the surrounding radio-electronic space and effectively distributing available resources [15].

Traditional approaches to interference analysis in wireless networks typically rely on the laboratory testbeds, software-based simulators, or physically separated hardware modules. Each of these methods has limited applicability in scenarios that demand simultaneous physical interference generation, flexible configuration, and real-time visualization of system behavior. This paper presents a hybrid approach involving physical interference generation with microcontrollers, software-based parameter control via WebSocket, along with real-time visualization and analysis of interference processes.

Results and discussion

Description of the hardware and software platform.

To implement a hardware and software platform for research and analysis of interference in wireless networks, it is necessary to design a transmitter, receiver and interference generator. Figure 1 shows the developed electrical circuits of the devices and the appearance in the assembly on the ESP32U microcontroller. Functionality tests were conducted, including checking all electrical connections, control response, and correct display of data.

In addition to hardware development, the creation of software for device control and data processing is of great importance. The software must be as flexible as possible to allow users to change test parameters such as frequency, signal strength, and interference characteristics. In addition, it is necessary to create a user interface for the platform that is easy to use and allows quick access to test results. Integration and testing of each part of the project are important steps. This includes checking device compatibility and testing performance under different operating conditions and load levels.

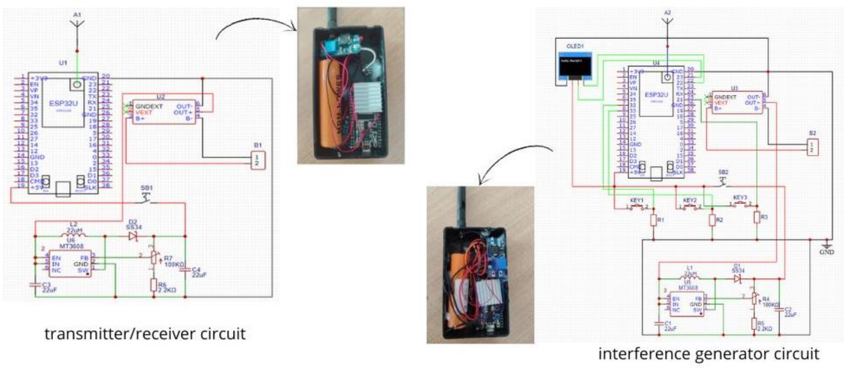


Figure 1 – Electrical circuit of devices

The architecture of interaction between modules is presented in Figure 2.

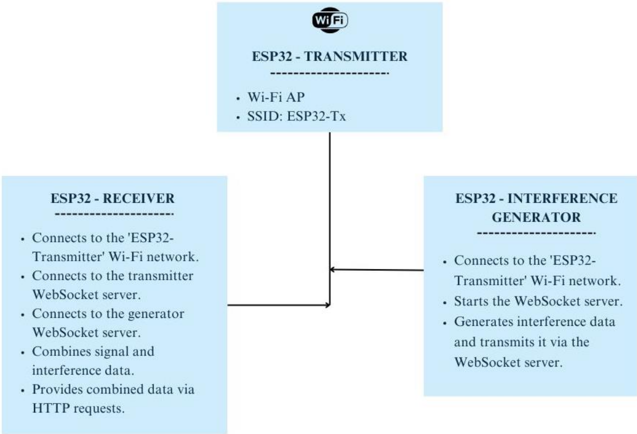


Figure 2 – Project architecture

The transmitter, receiver and jammer are developed based on the ESP32 microcontroller. The devices perform different functions. The transmitter creates a Wi-Fi access point, raises an HTTP server to serve web pages, and a WebSocket server to transmit signal data. It generates sine wave data and transmits it via WebSocket. The interference generator connects to the Wi-Fi network created by the transmitter and raises a WebSocket server to transmit interference data. It generates different types of interference depending on the mode selection and sends data via WebSocket. The receiver also connects to the transmitter's Wi-Fi network, connects to the transmitter's WebSocket server to receive signal data and to the interference generator's WebSocket server to receive interference data. The interaction between the components occurs as follows:

– the interference generator and receiver are connected to the Wi-Fi network created by the transmitter,

– the transmitter generates and transmits signal data through a WebSocket, and the interference generator generates and transmits interference data through its WebSocket,

– the receiver receives signal data from the transmitter and interference data from the interference generator, combines this data and provides it via HTTP requests.

The integration of the functionality of three modules – a transmitter, receiver and interference generator – into a single wireless network based on Wi-Fi using the WebSocket protocol for synchronous data exchange in real time is a technically new solution. Unlike existing disparate systems, this architecture ensures full coordination of the operation of all nodes with minimal delay in the transmission of control and measuring signals.

For this project, the task was to create a working system with reliable and stable software operation. The algorithms of operation of the receiver and transmitter is shown in Figure 3.

The transmitter in this system is responsible for generating sine waves that mimic analog signals in digital form. The main task of the transmitter is to send data regularly.

The developed program initializes the Wi-Fi connection, sets up IP addresses and starts the server. The data to be sent is generated and packaged in accordance with the transmission protocol, after which it is transmitted to the receiver. Special attention was paid to transmission efficiency and minimizing delays.

The receiver is used to receive data from the transmitter and, in some cases, from the interference generator. The program on this device is configured to receive data via Wi-Fi. This data is then processed and visualized as a graph on a web page, allowing the user to observe the signal processing process in real time. The received data is analyzed for errors and losses, which makes it possible to assess the quality of wireless communications. The analysis results are converted for subsequent study and comparison with theoretical interference models.

The interference generator is the main component of the system. It creates artificial interference by simulating various conditions that may be encountered in the operation of wireless devices. Interference is generated according to a specified algorithm, which can be configured in real time through the user interface. This allows you to simulate various network interference conditions, including changes in signal strength and channel switching. The implementation of the noise generator algorithm is shown in Figure 4.

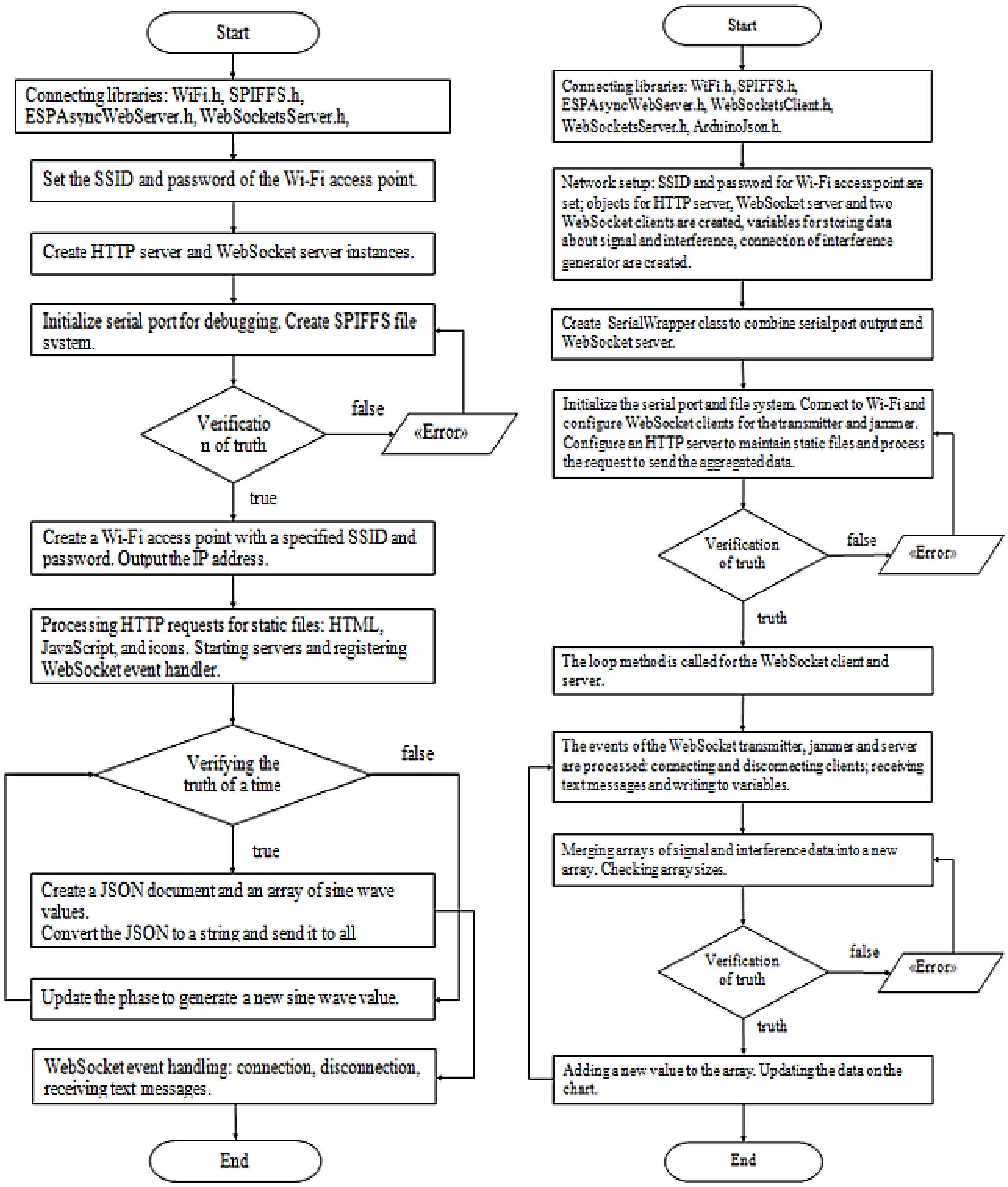


Figure 3 – Transmitter and receiver operating algorithms

The interference generator connects to a Wi-Fi network to be able to send data to the receiver. In this mode, it acts as a client on the network. WebSocket is used to send interference data to the receiver. This allows you to transmit data in real time and observe its effect on the processed signal. The code is responsible for generating random numbers that simulate interference and sending this data via WebSocket. The interference is generated as random values in a given range and can be adapted to simulate various types of noise or distortion.

One of the difficulties was synchronizing the operation of all three devices. It was possible to ensure effective interaction of devices via Wi-Fi using one network. Time synchronization between devices allows you to accurately measure the impact of interference on data transmission, which is critical for the reliability of experiments.

Implementation and experimental results. Figure 5 shows the appearance of the developed experimental stand.

The developed project studies amplitude modulation. The types of interference and their effect on the original signal are shown in Figure 6.

The developed simulator will allow one to observe the effect of interference on the initial signal and evaluate the output signal. This makes it possible to apply the most effective methods and approaches to eliminate interference in wireless data networks.

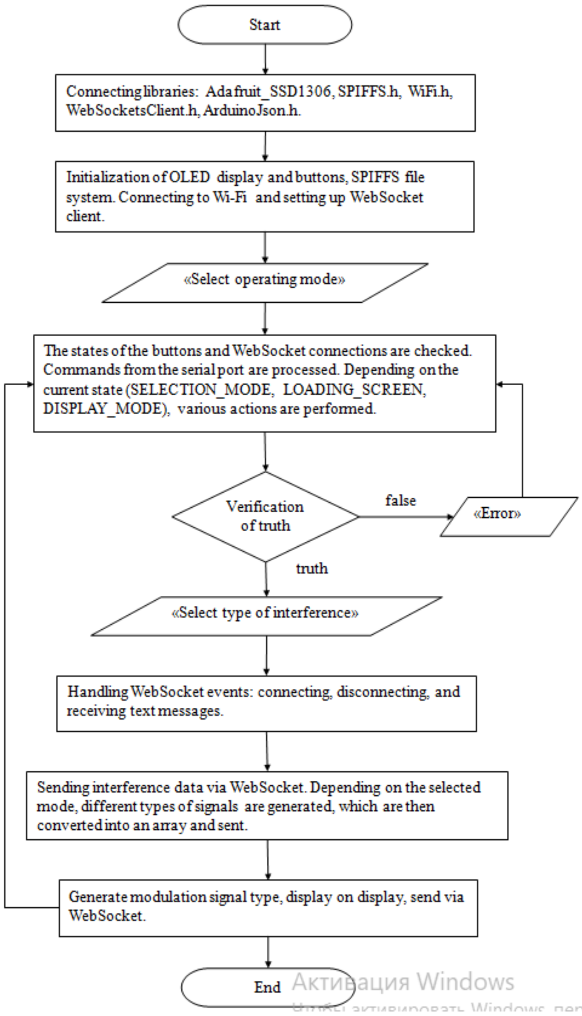


Figure 4 – The algorithm for implementing the interference generator

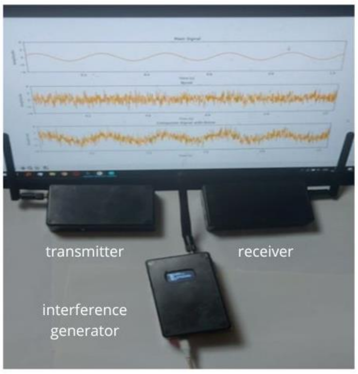
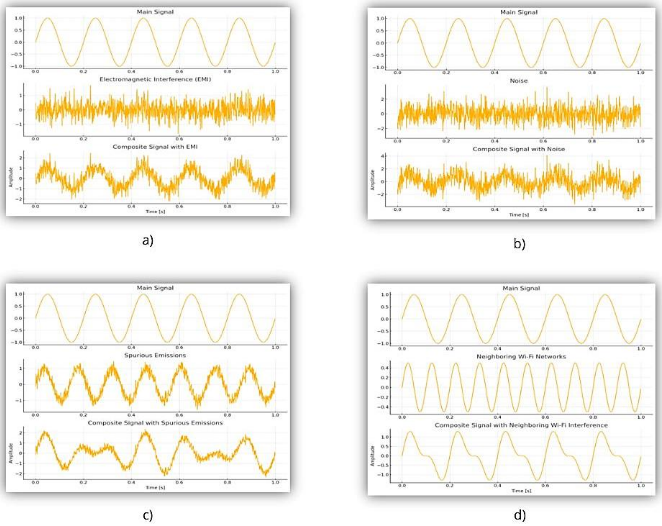


Figure 5 – Appearance of the experimental stand

The main results of the work can be formulated as follows:

1. The developed software allows you to simulate data transmission processes in a wireless network, as well as simulate the impact of interference on this process.
2. The developed hardware platform for generating interference allows you to create different types of interference and vary their parameters to assess their impact on the quality of communication in wireless networks.
3. Flexible architecture and the use of ESP32 microcontrollers have made it possible to create an effective tool for studying the behavior of wireless networks under various interference scenarios.

The stages of experimental testing demonstrated the adequacy of the model and the performance of the simulator for analyzing interference in wireless networks (Figure 6).



a) electromagnetic interference, b) interference from neighboring Wi-Fi connections,
c) spurious radiation interference, d) noise interference

Figure 6 – Simulation graphs of the original signal with various interference

Conclusion

Thus, a new approach to the development of a hardware-software platform for studying the stability of wireless data transmission networks is proposed, based on the integration of transmitting, receiving and interference-generating modules into a single controllable Wi-Fi network using the WebSocket protocol for real time synchronous data exchange.The developed platform allows simulating the influence of interference on the initial signal in wireless data networks. The hardware platform includes a transmitter, receiver and jammer, which are developed based on the ESP32 microcontroller. Software has been developed to control the parameters of each device and simulation scenarios. The programming language C++ and the development environment Arduino IDE were used. A software module has been implemented to analyze amplitude modulation and simulate the effect of possible interference on the signal during data transmission in Wi-Fi networks.

The architecture used allows implementing other types of modulation without the need to change existing connections between program components. The ESP32 microcontroller versions allow the platform to be adapted for research into Bluetooth and ZigBee technologies. This makes it a universal basis for developing and testing innovative wireless technologies.

The prospects for using a hardware and software platform for simulating and analyzing interference in wireless data transmission channels are significant, especially in the context of ever-increasing requirements for the reliability and stability of wireless communications. Manufacturers of IoT devices, wireless routers, radio modules and other equipment using radio frequency communications can use this platform to test the stability of wireless networks by simulating various interference scenarios, which is important for developing and improving communication protocols and data transmission methods in conditions of strong interference and unstable communications. When developing new wireless solutions, manufacturers can use this platform for preliminary testing of devices to identify and eliminate possible problems at the prototyping stage, which increases the quality and reliability of final products. Due to the availability of components, the platform can be used in educational and research laboratories to study the effects of interference, simulate signals and their modulations, which helps to develop skills in working with wireless technologies. Using the platform, you can develop and test interference filtering algorithms, adaptive transmission and modulation protocols, as well as conduct tests that will help optimize the stability of data transmission in conditions of external electromagnetic and radio frequency interference.

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ДЕРЕКТЕРДІ СЫМСЫЗ ТАСЫМАЛУ ЖҮЙЕЛЕРІНДЕГІ КЕДЕРГІЛЕРДІ МОДЕЛЬДЕУ ЖӘНЕ ТАЛДАУ

Мақалада заманауи сымсыз байланыс желілерінің тұрақтылығы мен сенімділігін зерттеуге арналған деректерді сымсыз тасымалдау жүйелеріндегі кедергілерді модельдеу және талдауға арналған бағдарламалық-аппараттық платформа ұсынылған. Зерттеудің өзектілігі Интернет заттары құрылғылары санының артуымен, Wi-Fi және 5G желілерінің қарқынды дамуымен, сондай-ақ сыртқы электромагниттік әсерлер жағдайында сымсыз байланыстың сапасы мен тұрақтылығына қойылатын талаптардың күшеюімен түсіндіріледі. Жұмыстың мақсаты – деректерді сымсыз беру арналарындағы әртүрлі кедергілерді генерациялау, модельдеу және талдау *үшін әмбебап құрал әзірлеу және процестерді нақты уақыт режимінде визуализациялау мүмкіндігін қамтамасыз ету.*

Платформаның аппараттық бөлігі ESP32 микроконтроллерлері негізінде жасалған таратқыштан, қабылдағыштан және кедергі генераторынан тұрады. Құрылғылар мен модельдеу сценарийлерін басқару үшін Arduino IDE ортасында C++ бағдарламалау тілінде бағдарламалық қамтамасыз ету әзірленді. Модульдер арасындағы деректер алмасу бірыңғай Wi-Fi желісінде WebSocket протоколы арқылы жүзеге асырылады, бұл сигналдарды нақты уақыт режимінде синхронды түрде беру мен өңдеуді қамтамасыз етеді. Жұмыста құрылғылардың электрлік сұлбалары, модульдердің өзара әрекеттесу архитектурасы және жүйенің жұмыс алгоритмдері ұсынылған.

Әзірленген платформа электромагниттік, шуылдық және көршілес арналардан туындайтын кедергілерді модельдеуге, амплитудалық модуляцияның деректерді беру сапасына әсерін талдауға және сымсыз байланыс арналарының тұрақтылығын бағалауға мүмкіндік береді. Эксперименттік зерттеулер ұсынылған модельдің тиімділігі мен жүйенің жұмыс қабілеттілігін растады. Платформаның икемді архитектурасы оны Wi-Fi, Bluetooth және ZigBee технологияларын зерттеуге бейімдеуге, сондай-ақ сымсыз желілердің кедергіге төзімділігін арттыру әдістерін әзірлеуде ғылыми және білім беру мақсаттарында пайдалануға мүмкіндік береді.

Түйін сөздер: *модуляция, кедергі, сымсыз желі, бағдарламалық қамтамасыз ету, ESP32, симуляция.*

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МОДЕЛИРОВАНИЕ И АНАЛИЗ ПОМЕХ В БЕСПРОВОДНЫХ СИСТЕМАХ ПЕРЕДАЧИ ДАННЫХ

В данной статье представлена программно-аппаратная платформа для моделирования и анализа помех в беспроводных системах передачи данных, ориентированная на исследование устойчивости и надежности современных беспроводных сетей. Актуальность исследования обусловлена стремительным ростом числа устройств Интернета вещей, развитием сетей Wi-Fi и 5G, а также повышением требований к качеству и стабильности беспроводной связи в условиях воздействия внешних электромагнитных помех. Целью работы является разработка универсального инструмента для генерации, моделирования и анализа различных типов помех в беспроводных каналах передачи данных с возможностью визуализации процессов в режиме реального времени.

Аппаратная часть платформы включает передатчик, приемник и генератор помех, реализованные на базе микроконтроллеров ESP32. Для управления устройствами и сценариями моделирования разработано программное обеспечение на языке C++ в среде Arduino IDE. Обмен данными между модулями осуществляется по протоколу WebSocket в единой сети Wi-Fi, что обеспечивает синхронную передачу и обработку сигналов в реальном времени. В работе представлены электрические принципиальные схемы устройств, архитектура взаимодействия модулей и алгоритмы функционирования системы.

Разработанная платформа позволяет моделировать электромагнитные, шумовые и межканальные помехи, анализировать влияние амплитудной модуляции на качество передачи данных и оценивать устойчивость беспроводных соединений. Экспериментальные исследования подтвердили работоспособность системы и адекватность предложенной модели. Гибкая архитектура платформы позволяет адаптировать ее для исследования технологий Wi-Fi, Bluetooth и ZigBee, а также использовать в научных и образовательных целях при разработке новых методов повышения помехоустойчивости беспроводных сетей.

Ключевые слова: *модуляция, помехи, беспроводная сеть, программное обеспечение, ESP32, симуляция.*

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Received 30.03.2026
Revised 19.05.2026
Accepted 20.05.2026

https://doi.org/10.53360/2788-7995-2026-2(22)-18

МРНТИ: 06.71.57

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МОДЕЛЬ ПРОГНОЗИРОВАНИЯ ОБРАЗОВАТЕЛЬНЫХ ТРАЕКТОРИЙ ВЫПУСКНИКОВ ШКОЛ НА ОСНОВЕ ДЕМОГРАФИЧЕСКИХ ДАННЫХ И МЕТОДОВ АНАЛИЗА БОЛЬШИХ ДАННЫХ

Аннотация: *В статье рассматривается разработка модели прогнозирования образовательных траекторий выпускников школ на основе демографических и социально-экономических факторов в Республике Казахстан. Актуальность исследования обусловлена необходимостью научного обоснования процессов распределения выпускников между различными формами дальнейшего обучения в условиях демографических изменений и трансформации системы образования. В работе использованы официальные статистические данные за период 1992-2025 гг., включая показатели рождаемости, уровня жизни населения и распределения выпускников по образовательным траекториям (высшее образование, среднее профессиональное образование, обучение за рубежом и альтернативные формы занятости). Для выявления взаимосвязей между демографическими и социально-экономическими показателями и выбором образовательной траектории применены методы корреляционного и дисперсионного анализа.*