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Analysis of Wireless Communication Protocols for Enhancing the Efficiency of Cognitive Telecommunications Networks Functionality

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ABSTRACT In the study, modern protocols and their specifications were analyzed and systematized. Advantages and disadvantages were identified, which are necessary for expanding the application possibilities of cognitive radio systems. Through the analysis of the technical characteristics of cognitive radio systems, the main factors of stagnation in various technological capabilities were discovered. It has been proven that IEEE protocols provide a critically important foundation for the standardization of cognitive radio systems, facilitating their compatibility and efficient use of the radio frequency spectrum. It has been substantiated that cognitive radio systems include optimization subsystems to ensure reliable communication. Specifically, the cognitive analysis subsystem is essential for effective monitoring of the radio frequency spectrum, enabling frequency adaptation in response to spectrum occupancy. The cognitive decision-making subsystem ensures optimal resource use through rational frequency distribution and transmission parameter adjustment. Adaptation and routing play a key role in ensuring reliable data exchange, while resource management and security measures strengthen the system's integrity and protection. The research demonstrated that the multi-level integration of subsystems opens new possibilities for enhancing the efficiency of radio frequency spectrum use in dynamically changing conditions. Thus, the implementation of modern protocols and technologies in cognitive radio systems is an important step towards creating more flexible and adaptive networks capable of effectively responding to changing conditions and user requirements. The analysis presented in the article demonstrates the necessity and effectiveness of applying innovative wireless communication protocols. These protocols significantly enhance throughput capacity and spectral efficiency, which, in turn, contribute to the optimization of network operations in "smart radio" systems across various applications – from military to commercial.

KEYWORDS cognitive radio, IEEE protocols, standards, specifications, adaptability.

I. INTRODUCTION

The continuous update of protocols and specifications for intelligent telecommunication systems (ITS) plays a strategically important role in ensuring national security in Ukraine and the development of global telecommunications [1-15]. Constant monitoring and updating of standards are critically important, as they significantly impact military communications which are crucial for the coordination of national defense. Additionally, these updates are necessary and have a decisive impact on civil connections between communities and businesses. They facilitate the development of the information space, economic growth, stimulate investments, and technological advancements, which are important for supporting innovation and digital transformation.

Thanks to the constant monitoring and analysis of modern technological capabilities and specifications, scientific research on this topic plays a key role in shaping future generations of telecommunications networks and services. The results of these studies are implemented in practice in the form of improved quality, accessibility, and security of telecommunication services, which are an integral part of life in a society closely integrated into the digital space.

Considering the various threats that Ukraine currently faces, particularly in conditions of martial law and the energy crisis, special attention must be paid to ensuring a high level of cybersecurity. The latest research and improvements in protocols and specifications, including those for cognitive radio systems (CRS), help protect critical infrastructure from cyber threats, which is essential for maintaining the state's defensive resilience.

A comparative analysis of the possibilities, advantages, and disadvantages of current specifications and protocol versions for smart radio systems allows us to substantiate the main trends in the development of telecommunications. It also enables conclusions to be drawn regarding the potential implementation of technologies that ensure a high level of accessibility, security, and efficiency, facilitate quality communication in the information space, and ease digital transformation.

Thus, scientific research in the field of cognitive systems is important due to its ability to influence political, social, and economic stability, meet society's needs for reliable and secure means of communication, and form the basis for the future development of the digital economy and society as a whole. The relevance of these studies is determined not only by current technological challenges but also by the strategic necessity to prepare for future innovative transformations in the field of telecommunications.

II. RECENT STUDIES AND PUBLICATIONS ANALYSIS

Despite the relevance and necessity of researching modern standards and their specifications, there is currently no unified systematization of them. Analysis of this problem was carried out by both domestic and foreign scientists who focused on various aspects of CRS. However, despite significant contributions, several key areas have been identified that remain underexplored.

Work [3] significantly expanded the understanding of modeling and distribution of bandwidth in cognitive relay networks, but did not cover the issue of the efficiency of spectrum use in conditions of high interference. The article [5] proposed a new approach to the encryption system using web pages as a cryptographic key, but did not consider the issue of data security when the content of the page is changed, which is necessary for use, including in smart radio systems. In [6], the authors focused on the integration of artificial intelligence in regional security technologies, revealing practical principles, but did not cover the wider context of the impact on the overall structure of network systems. In [8], the optimization of basic networks in audio analytics systems was investigated, but the issues of scalability and adaptability of these systems were neglected.

The article [9] analyzed the effect of imperfect information about the channel on the probability of failures in cognitive networks, but adaptation to changing conditions was not considered. In [10] load balancing mechanisms in networks based on software-defined infrastructure are considered, but the issue of integration with other security standards is not resolved.

In [12], the authors investigated various methods of spectrum detection in cognitive radio networks, which is the key to optimal use of the radio frequency spectrum. However, the integration of these techniques into general CRS has not been considered, which limits the possibility of practical application. In [14] and [15], scientists made specific contributions to data filtering and machine learning, but did not take into account integration into the general system of cognitive radio.

In view of the analysis of publications on the topic, it is relevant to conduct a study dedicated to the development of unified methods of systematization and optimization of protocols for CRS. This will allow not only to improve the efficiency of using the radio frequency spectrum, but to ensure a high level of adaptability and safety in dynamically changing conditions.

III. THE PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of the study is to analyze the impact of modern IEEE protocols and standards on the effectiveness of CRS, which is of key importance for adapting to changing communication conditions and security requirements. From a practical point of view, the results of the research make it possible to optimize the use of the radio frequency spectrum and increase the reliability of communications in critical conditions, in particular for military and civilian telecommunication systems. To achieve the goal, the following tasks are set:

– comprehensive analysis of subsystems of cognitive radio to optimize the efficiency of using the radio frequency spectrum;

– analysis of modern protocols and their specifications to determine the main trends and influences on the development of telecommunication technologies, with an emphasis on CRS;

– study of the influence of IEEE protocols on the optimization of the use of the radio frequency spectrum in smart radio systems in conditions of high traffic and interference.

The tasks will contribute to the achievement of the set goal, which will allow to significantly improve the parameters of the quality, availability and security of telecommunications, taking into account modern challenges and needs.

IV. RESEARCH MATERIALS AND METHODS

The object of research is CRS and their ability to adapt to the changing conditions of using the radio frequency spectrum.

The main hypothesis of the study is that the implementation of modern protocols and specifications can significantly improve the efficiency of the use of the radio frequency spectrum and provide a higher level of security in CRS.

It is suggested that existing spectrum detection methods can be optimized to better detect free frequency bands without interfering with the work of primary users. The study focuses on the analysis of existing protocols without considering potential intangible variables such as changes in the regulatory environment or political influences.

The results of the research carried out in the article are based on the analysis of scientific literature, modeling of CRS, assessment of bandwidth and efficiency of spectrum use using mathematical methods.

V. STUDY OF WIRELESS COMMUNICATION STANDARDS AND PROTOCOLS

ITS, also known as «smart radio», represent a new level of telecommunication technology development where smart algorithms and software are used to optimize network performance. These systems are based on the idea of a cognitive approach that enables systems to analyze the environment, take into account the parameters of the data transmission channel, and dynamically adapt their operation to changing transmission conditions [1].

One of the key characteristics of ITS is their cognitive aspect. They are able to perceive information from various sources and analyze network parameters and the external environment to make the best decisions regarding data transmission. This makes them flexible, i.e. capable of real-time optimization.

Another important characteristic is the ability to adapt to changing data transmission conditions. Intelligent systems can change transmission parameters such as frequency, power, and bit rate to ensure optimal performance in different environments. This is especially important in wireless networks where conditions can fluctuate. One of the main advantages of intelligent telecommunications systems is their ability to efficiently utilize limited resources such as radio frequency spectrum and bandwidth. They are designed to maximize the efficiency of the available resources, which allows for optimized network performance and increased productivity [2].

In general, intelligent telecommunications systems represent an extensive field of research and development that has the potential to change the way telecommunications are used and perceived. They can improve the availability, efficiency and security of communications and become a key component of the future digital world [3].

ITS include various subsystems and components to intelligently manage and optimize the use of radio frequency spectrum and communication resources. The main subsystems that usually exist in ITS include the following (Fig. 1, developed by the author's).

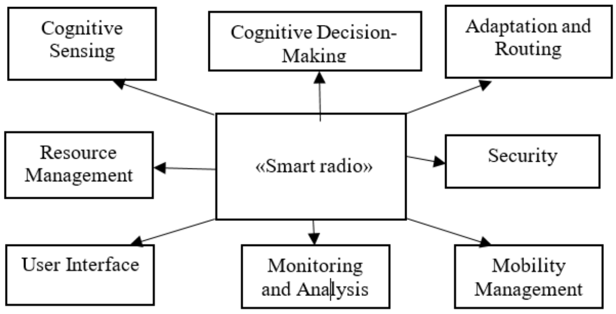

FIG. 1. Components subsystems of «smart radio».

1. Cognitive Sensing subsystem. The subsystem specializes in analyzing the radio frequency spectrum and performs several key functions that significantly improve the efficiency and reliability of real-time communication. First, the cognitive analysis subsystem is responsible for monitoring the radio frequency spectrum. It scans the surrounding spectrum, identifying available bands and frequencies. This analysis allows the system to identify free and occupied frequencies, which is critical to ensuring uninterrupted communication. When one band is congested or loaded with other users, the system can change the frequency to ensure stable communication. Second, the cognitive analysis subsystem can collect information about spectrum conditions in real time. This includes analyzing parameters such as signal strength, interference, noise, and other factors that can affect the quality and reliability of communication. With this information, the system can make decisions about the optimal mode of operation and adapt data transmission parameters to maximize performance. The main advantage of the cognitive analysis subsystem is its ability to learn and adapt on its own. It can detect changes in the radio frequency environment and learns to respond to them, ensuring optimal communication in different conditions.

To summarize, the cognitive analysis subsystem is necessary to ensure the efficient and reliable operation of modern telecommunication systems. It allows the system to understand and adapt to complex radio frequency conditions, ensuring the quality of communication and optimal use of available resources. bands and collecting information about spectrum conditions in real time [3, 12].

2. The Cognitive Decision-Making subsystem is a key component of modern telecommunications systems that plays an important role in improving the quality of communication and optimal use of resources. It operates at the highest level of analysis and management, using information received from the cognitive analysis subsystem to make decisions on a number of data transmission parameters. First, the cognitive decision-making subsystem determines the optimal frequency range for data transmission. Taking into account information about free and occupied frequencies, it can automatically select available bands, which reduces the likelihood of interference and improves the quality of communication. This is especially important in rail, airline, or urban wireless communications, where frequency conflicts can lead to serious problems.

Second, this subsystem makes decisions about signal modulation, transmitter power, and other transmission parameters. It analyzes the radio frequency environment, including noise and interference, and determines the optimal settings to maximize data transmission efficiency. This helps reduce power consumption and increase transmission speed, which is especially important for mobile devices and IoT systems.

The main advantage of the cognitive decision-making subsystem is its ability to adapt and learn. It can analyze the effectiveness of its decisions and adjust them in real time in accordance with changes in the radio frequency environment. This allows the system to operate at a high level of performance in different conditions and ensure the quality of communication, even in complex and variable environments.

As a result, the cognitive decision-making subsystem is important for optimizing the use of radio frequency resources, improving the quality of communication and ensuring efficient data transmission in modern telecommunication systems. It uses analysis and intelligent decision-making for automated control of transmission parameters, which makes it an important element in the development of future communication networks [4, 15].

3. Adaptation and Routing subsystem. This subsystem provides reliable and efficient data exchange in different network conditions. This subsystem includes two main aspects: adaptation and routing, and performs a number of important functions to optimize the data transmission process. Adaptation is a process that includes the ability of the system to adapt to changing network conditions and user requirements. The adaptation subsystem can change data transmission parameters, such as bit rate, signal coding, frequency channels, etc., depending on objective conditions such as channel change, interference, or distance to the receiver. This helps to ensure the best possible communication quality in all conditions and to optimize the use of available resources.

Routing is the process of determining the best path for data to travel on a network. The routing subsystem decides which routes and paths should be used to deliver data from a sender to a receiver. It takes into account various factors such as distance, path capacity, and other parameters to ensure the fastest and most efficient way to transmit data.

The adaptation and routing subsystem works with other system components, such as the cognitive decision-making subsystem, to ensure the best possible link quality and optimal use of resources. It can respond to changes in the network by dynamically changing transmission and routing parameters in real time.

The main advantage of the adaptation and routing subsystem is its ability to optimize telecommunication systems for different tasks and conditions, which allows for reliable and productive data exchange. It plays a critical role in ensuring high-quality communication and resource efficiency in modern communication networks.

4. Resource Management subsystem. This subsystem plays an important role in ensuring the optimal use of available resources, such as bandwidth, transmission power, as well as computing and network resources. The subsystem interacts with other system components and performs a number of important functions to ensure the efficient operation of the communication system. First, the resource management subsystem is responsible for allocating bandwidth and frequency resources to different users and services. It controls access to resources and ensures fair and efficient allocation, reducing conflicts and interference between users. Second, this subsystem is responsible for controlling the power of transmitters. It can adjust the signal strength depending on the distance to the receiver, channel quality, and other factors. This helps to reduce power consumption and interference, as well as increase battery life on mobile devices. Third, the resource management subsystem coordinates computing resources for data processing and transmission. It distributes tasks between computing nodes and servers to ensure optimal system performance. This is especially important in cloud computing and IoT networks, where large amounts of data need to be processed quickly. An important characteristic of the resource management subsystem is its ability to dynamically adapt to changing conditions. It can analyze network conditions and decisions of cognitive analysis and decision-making subsystems, and then respond to changes to ensure maximum performance and quality of user experience [9, 14]

5. Security subsystem. It is one of the most critical and integral components, as it is responsible for protecting information and ensuring the confidentiality, integrity and availability of data in the modern digital world. Communication and data exchange systems face various threats and challenges, including cyberattacks, information leaks, espionage, and other attacks. The security subsystem is designed to prevent such threats and ensure the reliability of communications and data. The main functions of the security subsystem are user identification, authentication, authorization, and data encryption. This means that the system verifies the user's identity, determines what actions they can perform, and ensures the confidentiality of data during transmission. This approach allows restricting access to data only to authorized users and protecting it from unauthorized access [5, 6].

The security subsystem also includes measures to detect and respond to cyberattacks. It monitors the network for anomalies and potentially harmful activity, and if an attack is detected, it can automatically suspend access to the system or notify the administrator for further response. It is especially important to ensure security in IoT networks, where a large number of connected devices can be vulnerable to attacks. In this case, the security subsystem helps to protect these devices from unauthorized access and use [6].

6. Monitoring and Analysis subsystem. Provides continuous monitoring of the network and allows you to track various parameters to ensure the quality and efficiency of communication. This subsystem includes resource monitoring, traffic analysis, anomaly detection, and many other functions. One of the key functions of the monitoring subsystem is to constantly monitor the status of network resources, such as bandwidth, frequency resources, computing resources, etc. Monitoring allows you to detect malfunctions and overloads in time, which helps to avoid failures and ensure continuous network operation. The subsystem is also responsible for analyzing network traffic. It measures the amount of data transmitted, determines traffic characteristics such as transmission speed and latency, and examines traffic patterns. This information is useful for understanding resource utilization, detecting anomalies, and optimizing network performance [7, 8]. Additionally, the monitoring and analysis subsystem provides anomaly detection in the network. It can detect unusual activity, unauthorized access, or attacks on the network. This ability helps to detect security issues and other threats in time. An important characteristic of the subsystem is its ability to learn and adapt. It can improve its analysis algorithms based on accumulated data and respond to changes in the network. This makes the subsystem dynamic and able to adapt to growing demands and new types of threats [8]

7. User Interface subsystem. This is a subsystem that interacts with the user and provides the ability to manage the system and receive information. The user interface is designed to make interaction with the system convenient, efficient and intuitive for users. One of the key functions of the user interface subsystem is to provide access to the system functionality. This may include entering commands, setting parameters, sending and receiving messages, etc. A properly designed interface should be intuitive and user-friendly, even for those without specialized training.

Another important aspect of the user interface is the visual representation of information. The display of data and system status should be clear and easy to read. This can include graphical elements such as charts, graphs, and other visual components that help the user analyze data and make decisions.

The user interface subsystem may also include capabilities for interacting with the system through voice commands, gestures, or touch screens, making it more versatile and accessible to different types of users and situations. An important characteristic of the user interface subsystem is its ability to be customized and personalized. Users should be able to customize the interface according to their needs and preferences to make their interaction with the system more efficient and comfortable [9, 11].

8. Mobility Management subsystem. Responsible for managing mobile users and their devices in the network. This subsystem is designed to provide continuous and efficient communication even when users move within the network, which is especially important in today's world where user mobility is a standard. One of the key functions of the mobility subsystem is to track the location of mobile users. It constantly monitors the location of users and their devices to ensure uninterrupted communication. The subsystem updates information about the user's location and ensures that calls and data are forwarded to their current location [12].

Additionally, the mobility subsystem includes the functions of registration and authentication of mobile devices and users in the network. Every time a mobile device connects to the network or changes its location, the system performs a registration process to identify the user and authorize him or her to use the network. This is important for security and access control.

The mobility subsystem also has an important aspect of network resource management, as it helps to optimize the use of network resources when changing

Analysis and knowledge of specifications and standards for ITS or «smart radio» play an important role in modern wireless communications. First, standardization and compliance are fundamental to ensuring interoperability and interoperability between different ITS components and systems. This means that different companies and developers can create equipment and devices that work together and comply with common standards. Knowing these standards helps ensure that systems will interact effectively with each other.

Second, specifications and standards define rules for managing radio frequency resources and spectrum use. This is especially important in a context of limited radio frequency resources, where each network has to compete for access to spectrum. Knowledge of standards helps to optimize resource utilization and reduce possible interference.

In addition, standards include norms and requirements for safety and security in ITS. Knowledge of these standards is important to ensure the confidentiality and integrity of data, as well as protection against potential threats and attacks. Understanding and adhering to specifications and standards also fosters innovation and development of ITS. It allows developers to introduce new technologies and features that expand the capabilities of wireless communications [10, 14].

In addition, it is important to ensure interoperability with other networks and systems, as well as to provide a high quality of service for users. In general, standardization and specifications play an important role in creating reliable and efficient smart telecommunication systems, which are the basis for the future of wireless communications.

The analysis of the use of various protocols for smart telecommunication networks is quite broad and is actively researched in the field of information technology and telecommunications. This topic has become particularly important with the development of the concept of «smart radio» and cognitive technologies in telecommunications. Research is based on the analysis and comparison of various aspects of protocols, standards and technologies, such as [9].

1. Spectral efficiency. Research is aimed at determining which protocols make the best use of the radio frequency spectrum to ensure maximum throughput and minimal inter-channel interference.

2. Energy efficiency. We analyze which protocols allow for the economical use of energy in wireless networks, especially in the context of Internet of Things (IoT) networks.

3. Quality of service (QoS). The research includes the analysis of protocols that provide a high level of quality of service, especially for applications with high requirements for low latency and high throughput.

4. Security. In the context of the growing threat of cybersecurity, research examines which protocols provide the highest level of security to protect data and networks in intelligent telecommunications systems.

5. Application scenarios. Researchers are investigating which protocols are best suited for specific application scenarios, such as mobile communications, IoT, wireless networks.

6. Standards and regulation. Research includes analysis of current standards and regulations that affect the use of different protocols in specific regions or industries.

The development of innovative technologies and standardization in the field of smart radio is active, and new protocols are emerging very quickly to help optimize the use of radio spectrum and improve wireless communications. Let's analyze the current protocols in the field of cognitive radio.

1. IEEE 802.22 (WRAN – Wireless Regional Area Network). The most famous wireless networking protocol that specializes in the use of white spaces is in TV White Space bands using cognitive radio technologies. It allows you to dynamically utilize vacant channels, adaptively adjust data transmission parameters, and use geolocation for efficient spectrum utilization [3, 15]. Common IEEE 802.22 specifications are presented in Table 1 (developed by the author's).

The main feature of IEEE 802.22 is dynamic access control, which requires devices to detect free frequencies and avoid conflicts with other systems. The standard also uses cognitive analysis to efficiently utilize spectrum resources and includes resource management and security mechanisms to protect data and the network. This makes IEEE 802.22 ideal for providing Internet access in rural and remote areas where free spectrum is available. This protocol is most often used for «smart radio» and it has certain advantages and disadvantages. The biggest advantage is the efficient use of white spaces. IEEE 802.22 allows the use of frequency bands that are not used in a given region or time, which allows for efficient use of spectral resources. The system also has a long data transmission range, making it ideal for wireless access in regions with low population density or in remote areas.

TABLE 1. IEEE 802.22 protocol specifications.

Specification	Characteristics
IEEE 802.22-2011	Standard for WRANs that utilizes TV white spaces to deliver broadband in rural areas without disrupting TV broadcasts
IEEE 802.22.1	A working group that studies the use of IEEE 802.22 technology in the radio frequency spectrum bands from 54-862 MHz for wireless Internet access in different regions of the world.
IEEE 802.22.3	A working group that considers extensions and additions to IEEE 802.22 technology, including wideband operation and network performance.
IEEE 802.22.2	A working group dedicated to the development and standardization of methods for evaluating and managing mixed signals that use the white areas of the radio frequency spectrum.
IEEE 802.22.3a	The working group focuses on improving network performance and adding support for new features and services that require higher data rates and advanced capabilities.

A significant advantage of IEEE 802.22 is the ability to use cognitive analysis to identify available frequency bands and avoid interference, which helps to ensure stable and reliable communication, as well as flexibility and adaptability of the system to changes in the spectral environment with the ability to use available resources at the maximum level of efficiency.

As for the disadvantages of IEEE 802.22 (WRAN), the most significant are: the complexity of implementation due to the need to manage white zones and conflicts over access to spectrum resources, and the inability to compete with existing networks. Existing wireless networks, such as Wi-Fi and mobile networks, may have an advantage in areas where IEEE 802.22 is struggling to access white spaces [1, 10].

In addition, IEEE 802.22 (WRAN) requires hardware support, which requires devices to be equipped with the appropriate hardware and software, which can lead to high costs. And there may be cooperation and security issues with other services that may require free access to white spaces.

IEEE 802.22 is a wireless network access standard designed for use in regional networks with long range coverage. However, there are cases and circumstances where the use of this standard may be difficult or impractical.

In large cities and areas with high population density where many other networks and devices exist, WRAN may face limited spectrum resources and interference, making it difficult to use due to conflicts with the objectives of existing video relay services. In addition, this standard may not provide the high bandwidth that users may require, especially in areas with a high volume of demanding applications. Licensing and access issues are an additional challenge for WRAN, as they require appropriate permissions and can complicate the network deployment process. Additionally, setting up infrastructure and equipment for WRAN can be costly and difficult to implement, especially in remote or inaccessible locations. Mobile connectivity may also be limited, as this standard is typically designed for stationary devices. Availability and support of equipment for WRAN may be less than for other wireless networks such as LTE or 5G. This limits users and operators who may prefer more common technologies.

2. IEEE 1900 includes a number of standards that define the architecture and guidelines for radio resource management and spectrum policy for wireless communication systems [1]. These standards are designed to make efficient use of the radio spectrum and to ensure that the spectrum is shared by different users and systems. The key standards of the «family» are aimed at solving the problem of insufficient spectrum resources for the growth of wireless communication systems and developing methods of spectrum regulation (Table 2 developed by the author's).

TABLE 2. Specifications IEEE 1900.

Specification	Characteristics
IEEE 1900.1	The standard describes the architectural aspects of DET systems, including the separation of functions between the system and the network, management of resource information, and support for quality of service and security management.
IEEE 1900.2	The standard defines methods and procedures for managing the network and resources, including algorithms and principles, quality of service, and interrupt handling in DET systems.
IEEE 1900.4	The standard covers recommendations for spectrum management and control in DET systems.

In general, these standards are aimed at integrating various wireless sensors and devices with RFID systems, defining the architecture and interfaces for their joint operation.

IEEE 1900 subsystems include device management, data processing and transmission, and data monitoring and analysis subsystems. This allows different devices to work together and exchange information.

One of the main advantages of IEEE 1900 is the efficient regulation and management of the radio spectrum. This means that users can adapt to changes in the spectral environment and efficiently utilize free frequencies for wireless communication. Second, IEEE 1900 promotes spectrum sharing among different users and systems. This helps to optimize the use of the radio spectrum and reduce interference to wireless communications. The third advantage is the ability to dynamically manage radio resources in real time. This improves network performance and user experience. In addition, IEEE 1900 is designed with cognitive radio and smart spectrum usage in mind, which helps devices adapt to spectral conditions and reduce spectral conflicts. Additionally, these standards can be used to support intelligent telecommunications systems that require dynamic radio resource management and network optimization. The IEEE 1900 protocol is designed to comply with international spectrum regulations, which promotes global interoperability and international cooperation in the field of wireless communication systems.

The IEEE 1900 standard, despite its advantages in regulating and optimizing the use of the radio frequency spectrum, in practice faces significant shortcomings. First, the complexity of implementation, which requires significant resources and deep technical expertise. This makes widespread adoption of IEEE 1900 difficult, especially for enterprises with limited technical capabilities or in countries/regions with a low level of technological development [8].

Secondly, the relative complexity of understanding the technical aspects of the IEEE 1900 standard. The complexity of the terminology and procedures complicates the assimilation and application of the standard, which reduces its attractiveness and practical utility.

Also, in the fast-paced world of technology, standards such as IEEE 1900 can quickly become obsolete. Innovations in the telecommunications industry occur at an incredible speed, and standards that do not keep up with these changes may become insufficiently adaptive to new requirements and technologies. This lag can make it difficult to integrate new technological solutions, limiting the potential for innovation and development [10].

3. IEEE 802.11 (Wi-Fi) is a widespread protocol for wireless local area networks (WLAN) (Table 3, developed by the author's). The table below provides an overview of the major versions of the IEEE 802.11 protocol, often referred to as Wi-Fi, which is crucial for wireless local area networks (WLAN).

TABLE 3. Major versions of the IEEE 802.11 standard.

Specification	Characteristics
IEEE 802.11b	Defines a wireless standard that operates at a frequency of 2.4 GHz and supports data rates of up to 11 Mbps. One of the earliest versions of Wi-Fi.
IEEE 802.11a	This standard also operates at 5 GHz, but supports higher data rates than 802.11b, up to 54 Mbps.
IEEE 802.11g	A standard that combines the characteristics of 802.11b and 802.11a and operates at a frequency of 2.4 GHz. The data transfer rate is up to 54 Mbps.
IEEE 802.11n	Defines MIMO (Multiple Input, Multiple Output) technology to increase data transmission speeds and improve network coverage. It can support speeds up to 600 Mbps.
IEEE 802.11ac	A standard for 5 GHz wireless networks that supports even higher data rates, up to 3.47 Gbps.
IEEE 802.11ax	One of the latest versions that improves network performance and efficiency, particularly in conditions of high device density and load.
IEEE 802.11 ay	A version that operates at a frequency of 60 GHz and is designed for high-speed wireless communication over short distances, in local networks
IEEE 802.11 ah	The standard, which is designed for use in IoT networks, requires less energy to connect devices to the network.

Each entry details a different iteration of the standard, noting their operational frequency, data rate capabilities, and other key characteristics that distinguish each version.

This comprehensive summary allows for a clear comparison of how Wi-Fi technology has evolved to meet increasing demands for faster and more reliable wireless communication. It captures the progressive enhancements that have been made from early standards focused on basic connectivity to newer versions designed to support high-density environments and intensive data usage scenarios. [9, 13].

In terms of basic characteristics, IEEE 802.11 is not a standard for smart radio. However, developers have made a number of extensions and improvements to the Wi-Fi standard to support some cognitive radio functions or channel management (protocols are not presented in Table 3 [4]. Namely:

– IEEE 802.11h. This is an extension of the IEEE 802.11 standard designed to work in regions with limited access to the radio frequency spectrum. It includes mechanisms to dynamically detect and avoid interference by changing communication parameters, such as transmit power;

– IEEE 802.11af. This protocol defines rules for the use of TV White Space for wireless access. It includes mechanisms for detecting and utilizing vacant channels in white space using cognitive radio;

– IEEE 802.11y. This protocol extends the capabilities of the IEEE 802.11 standard to work in certain frequency bands, including TV White Space bands. It uses cognitive radio to manage channels and ensure spectrum efficiency.

The considered extensions of the Wi-Fi protocol include elements of cognitive radio.

The advantages of IEEE 802.11 include: widespread adoption and support, enabling wireless Internet access and resource sharing in: offices, cafes, airports, and home networks. It supports high data rates and reliable communication, making it ideal for video streaming and other demanding applications.

IEEE 802.11 does have some drawbacks. First of all, Wi-Fi frequency bands can be contaminated and overcrowded, which can lead to a drop in data rates and interference. To ensure maximum performance, complex configuration and management is sometimes required. Another disadvantage is the limited coverage area of Wi-Fi access points, which may require many access points to cover large areas, which can be costly and difficult to install.

IEEE 802.11 is the most common standard for wireless network access in the world today. However, there are circumstances and situations where using Wi-Fi may not be possible or effective. In remote areas such as mountains, deserts, or remote islands where there is no infrastructure for Wi-Fi signal transmission, creating a Wi-Fi network may not be possible. The lack of infrastructure and access to the Internet via Wi-Fi creates limitations for residents and businesses in these regions.

Additionally, in large cities and areas with high population density, there may be a problem of radio frequency conflict, as a large number of Wi-Fi networks and wireless devices can overload the spectrum resource, leading to poor performance and excessive interference. In such conditions, Wi-Fi may not be effective in providing reliable and fast network access.

There are also restricted areas where the use of Wi-Fi for security purposes may be prohibited, such as in military installations or restricted areas. Even when Wi-Fi is available, long-range communication requirements may require specialized technologies, such as microwave or satellite communications.

4. LTE (Long-Term Evolution). It is a mobile communication technology characterized by high data transfer speeds and reduced latency, making it one of the most advanced technologies in the industry [11, 14]. The main goal of LTE was to improve the quality of mobile communication services and provide users with fast and reliable access to the Internet and other multimedia services. Today, LTE includes various versions, the main ones of which are presented in Table 4 (developed by the author's).

TABLE 4. Characteristics of LTE versions.

Version	Characteristics
LTE Release 8	Known as the first commercial release of LTE, it was adopted in 2008. It supports speeds of up to 100 Mbps downlink and 50 Mbps uplink, and was aimed at improving data transfer, energy consumption, and network efficiency.
LTE-Advanced (LTE-A) (Release 10 and above)	This version contains a number of enhancements and extensions to increase data speeds and improve network performance. LTE-A supports more broadband channels, has coordinated multiple input-output (CoMP), and other technical improvements.
LTE-Advanced Pro (LTE-A Pro)	The version includes the following improvements: support for high-frequency bands, improved scalability, and improved service quality.
5G-NR (New Radio)	Although 5G-NR is a separate standard, it is significantly related to the development of LTE and the development of fifth generation (5G) wireless networks. 5G-NR includes a number of new features and technologies that allow for higher throughput, lower latency, and improved support for a large number of connected devices.

Although LTE is not a direct «smart radio» technology, it uses certain techniques that can be associated with cognitive radio in certain contexts. These include: –

– spectrum scanner. In LTE, mechanisms exist to determine available radio frequency resources and intercept environmental information such as neighboring base stations. This can be useful for adapting to changing channel conditions;

– multiplication of connections. LTE can support the CoMP (Coordinated Multi-Point) technique, which allows resources from different base stations to be combined to improve the quality of communication. This can be used to better manage the radio frequency spectrum and minimize interference;

– dynamic resource management. LTE supports various methods for resource management, such as frequency and power allocation changes, modulation and coding adaptation, interference control, etc. This allows LTE devices to adapt to changing channel conditions.

However, it is important to note that LTE is not a typical cognitive radio technology. Cognitive radio implies a more advanced adaptation to vacant spectrum resources and the ability to detect vacant channels in a wider frequency range, which is not limited to its own licensed band. In addition, LTE does not have mechanisms for monitoring and changing large parts of the radio spectrum, which is typical for cognitive radio.

Specification LTE is a standard for mobile communications and is used for 4G and 5G networks. It defines the rules for high-speed data transmission in wireless networks. Subsystems - LTE includes subsystems for resource management, network monitoring and analysis, as well as subsystems for mobility management and network elements [12].

One of the main advantages of LTE is the significantly improved data transfer speeds compared to previous generations of mobile communications. This allows users to quickly download files, stream videos, and use demanding applications such as video calling and online gaming. In addition, LTE has low latency, making it ideal for real-time applications. Low latency is important for video calling, voice search, and other applications where instant communication is important. LTE networks typically have wide coverage, making them available in different geographical areas.

LTE also supports the simultaneous connection of many devices. This is especially important for use in distributed Internet of Things (IoT) networks and for providing connectivity for many users.

In addition, LTE technology is constantly evolving.

Standards, such as LTE Advanced and LTE Advanced Pro, are being introduced to further improve data speeds and capabilities.

The main disadvantages of LTE include: high infrastructure costs, as building and maintaining LTE infrastructure can be costly for mobile operators, and limitations for application. In large cities and areas with high population density, where the demand for wireless Internet access is extremely high, LTE network congestion may occur.

5. IEEE 802.15.4 – Low-Rate Wireless Personal Area Networks (LR-WPANs) protocol [14]. This protocol is designed to build efficient networks that require low energy consumption and low data rates. There are several varieties of IEEE 802.15.4 [9], which are presented in Table 5 (developed by the author's).

TABLE 5. Characteristics of IEEE 802.15.4 versions.

Version	Characteristics
IEEE 802.15.4a	This version defines mechanisms for working in Ultra-Wideband (UWB) bands and transmitting signals with high bandwidth and high location accuracy.
IEEE 802.15.4b	Extension of the standard for short-range operation with greater emphasis on low power consumption.
IEEE 802.15.4c	Expands the capabilities of the standard to operate in higher frequency bands.
IEEE 802.15.4g	The protocol is designed to operate in TV White Space bands, which requires the use of cognitive radio technologies to manage spectrum resources.

While IEEE 802.15.4g is specifically designed to operate in the TV White Space bands and requires cognitive management of spectrum resources, other varieties of IEEE 802.15.4, such as IEEE 802.15.4a, 802.15.4b, and 802.15.4c, do not have built-in cognitive radio mechanisms. They are specialized for specific applications, such as sensor networks or wireless control systems. Therefore, the ability to use cognitive radio technology depends on the specific type of IEEE 802.15.4 protocol and its purpose.

6. IEEE 802.16 (WiMAX – Worldwide Interoperability for Microwave Access) is a wireless Internet access technology designed to provide roaming and point-to-point access over long distances [1, 3, 8]. The main specifications of IEEE 802.16 are presented in Table 6 (developed by the author's).

TABLE 6. Main specifications of IEEE 802.16 (WiMAX).

Specification	Characteristics
IEEE 802.16 - 2004	The first version of the standard that defines wireless access technology over medium and long distances. This standard supports the microwave range and uses OFDM.
IEEE 802.16e-2005 (Mobile WiMAX)	This version expanded the standard to support mobile devices, allowing connectivity on the go. It also increased the supported data rates.
IEEE 802.16m (WiMAX 2.0)	This version has expanded network capabilities, improved service quality, increased data transfer speed and provided support for mobile devices.
IEEE 802.16j (Multihop Relay)	This version of the standard includes support for relay technology to improve coverage and increase network efficiency.
IEEE 802.16p (Fixed Wireless Access Interface)	This version of the standard covers specifications for fixed wireless broadband Internet access systems.
IEEE 802.16s (Management Plane Procedures)	This version defines the network management and control procedures that support network operations.
IEEE 802.16t (Management Information Base)	This version of the standard defines the management information base for the IEEE 802.16 network.

The IEEE 802.16 standard was not specifically designed for smart radio systems, but in practice it is used in the context of cognitive radio with some limitations. Built-in spectrum scanning tools help identify available RF resources and determine their availability for use. In cognitive radio mode, IEEE 802.16 can provide mechanisms for dynamic resource management by changing communication parameters depending on current conditions and requirements [9, 15]. Some IEEE 802.16 implementations may include support for reprogrammable antennas that can adapt to current channel conditions [8]. Reprogrammable antennas, also known as «smart antennas», can include technologies such as:

1. Antennas with electronic beam control (Beamforming). The technology allows you to dynamically change the direction of the antenna beam to improve signal quality and reduce interference. It can be used in IEEE 802.16 implementations to improve transmission efficiency in mobile and stationary modes.

2. Adaptive antennas (Adaptive Antennas). Such antennas automatically adapt their parameters according to the channel conditions, which includes changing the angle of inclination, polarization and other characteristics to maximize the quality of the connection.

The main advantage of WiMAX is high data transfer rates. In addition, WiMAX supports both point-to-point access for connecting devices and broadband access for connecting a group of devices or entire networks. WiMAX also works on different frequencies, supports the operation of stationary and mobile devices.

Although WiMAX (IEEE 802.16) has a number of technological advantages, it has not been able to gain mass adoption like LTE and the latest 5G standards. There are several reasons for this, namely:

1. High competition from LTE and 5G, which have strong support from major mobile operators and equipment manufacturers, unlike WiMAX.

2. Licensing issues. Launching WiMAX networks requires spectrum licenses, which can be expensive or difficult to obtain.

3. Bandwidth limitation. Although WiMAX provides high data rates, it can have limited bandwidth compared to LTE and 5G, especially in high user load conditions, resulting in reduced quality of service during peak times.

4. Radio frequency conflicts. WiMAX uses frequencies that may overlap with other services.

These and other factors have contributed to WiMAX's failure to become the dominant technology for wireless access, despite its technological advantages, particularly in cognitive radio applications.

One of the main advantages of WiMAX is its high data transfer speeds. This allows users to quickly download files, watch videos online, and use demanding applications. Another important characteristic is the ability to support both point-to-point access for connecting individual devices and ford access for connecting a group of devices or entire networks. WiMAX also has the ability to operate at different frequencies, which makes it more versatile.

This technology supports both fixed and mobile devices, including mobile phones. At the same time, it should be borne in mind that WiMAX is not as widely used as LTE and 5G. Under certain conditions and depending on specific needs and circumstances, the use of WiMAX can be difficult due to radio frequency conflicts, licensing issues, limited bandwidth, and financial constraints. Typically, these protocols include various subsystems and components to ensure network operation, including resource management, monitoring, security, data processing, and more [11].

TABLE 7. Uniform Assessment, IEEE «Smart Radio» Params.

Protocol	IEEE 802.22 (WRAN)	IEEE 1900	IEEE 802.11	LTE	IEEE 802.16 WiMAX	IEEE 802.15.4g TV White Space
Frequency range	Ultrahigh (UHF), 54 – 862 MHz	CR, DSA; UHF, HF, and microwave band	2,4 GHz – 5 GHz, 6 GHz (WF 6E)	700, 800, 1800, 2100, 2600 MHz	2,3–2,7, 3,5, 5,8, 10–66 GHz	54 – 698 MHz
Spectral efficiency	High: OFDM	CR, DSA; on QAM, OFDM	OFDM, QAM	High: OFDM, MIMO		High. TV White Space
Modulation	QPSK, 16-QAM, 64-QAM	QAM, OFDM	QPSK, 16-QAM, 64-QAM, 256–QAM		QPSK, 16-QAM, 64-QAM, 256–QAM, BPSK	QPSK, 16-QAM, 64-QAM, 256–QAM Q-QPSK
Low-noise operation	Stab., ext. range, red. interf., spect. opt.	Network Param. Optimization	AMC, Beam-forming, MIMO TX Power, Conv. Place-ment	Low transmission frequency	Freq. Read-aptation	Long range, low power, stable connection
Geo-location	ECC, AFC, TDOA	ECC, A-GPS, TDOA, RSSI	Trilat, Fingprint (W-F/ BT), GPS, IP FP, Multi-AP	Cell ID, A-GPS, E-OTD, Trilat, OTDOAW-F, BT	Signal Location, GPS & WiMAX, Analysis, Multilat	GPS/Device, BS, Data Storage, TVWS Regulation
			Encryption, authentication			
Security	MAC filtering, VPN, IPsec, AES	AES, EAP, RADIUSPKI	WEP, WPA, WPA2, WPA3, WPA-PSK, WPA-Enterprise802.1X	AES, EAP, SNOW 3G, MME, HSS, KASUMI, UE, EPC, KDF	WEP, WPA, WPA2, WPA3 VPN. 802.1X.	AES-CCM, HMAC, CCM* (Cipher-based Message Authentication Code)

In Table 7, developed by the authors, a comprehensive comparative analysis of various protocols, their versions, and specifications in the field of intelligent radio systems is presented. This overview highlights their unique contributions, characteristics, and functional attributes, underscoring the diverse capabilities and technological innovations within this evolving field.

The considered protocols, their versions and specifications made it possible to identify a compatible single principle in the field of cognitive radio, which consists in the ability of devices and networks to recognize and adaptively use available radio frequency resources, taking into account limitations and license conditions. Continuous monitoring, analysis, improvement of protocols for «smart radio» allows to adapt telecommunications to changing spectrum conditions, improve efficiency, ensure security, support new technologies and reduce interference.

In smart radio systems under conditions of high load and interference, the study of the impact of IEEE protocols on the optimization of the use of the radio frequency spectrum requires a comprehensive method, covering theoretical analysis, modeling and experimental verifications. The adaptive algorithm of this method includes the following stages [7, 15].

1. Theoretical analysis of existing IEEE protocols for cognitive radio, such as IEEE 802.22 and others described above, which define standards for wireless networks using empty television frequencies. This standard particularly emphasizes cognitive functions to identify and use free frequencies without interference for primary users.

2. Modeling. Using simulation software such as MATLAB or NS3, models of different radio spectrum usage scenarios can be created to evaluate the impact of protocols on performance under high traffic conditions. This includes modeling noise, interference, and other external factors that may affect signal transmission.

3. Experimental tests. Experimental tests can be performed using specialized hardware, such as spectrum analyzers, to realistically assess the impact of protocols on spectrum efficiency. The tests will allow you to collect data on frequency, signal strength, interference and other critical parameters under controlled conditions.

4. Data analysis. The collected data is analyzed to determine how well the protocols optimize spectrum usage. Machine learning and statistical analysis methods are used to identify trends, determine optimal settings, and formulate recommendations for improving protocols.

5. Checking the adequacy of the models. The last stage includes the comparison of model results with real experimental data to check the adequacy and accuracy of theoretical predictions. This is important to ensure the reliability of the proposed improved protocols.

These activities provide a comprehensive understanding of the impact of IEEE protocols and standards on optimizing the use of radio frequency spectrum in CRS, which is key to improving efficiency and reliability in today's telecommunications environment.

VI. DISCUSSION OF RESEARCH RESULTS

During the research, it was proven and substantiated that the use of modern IEEE standards and protocols contributes to increasing the spectral efficiency and bandwidth of CRS. In particular, the use of protocols such as IEEE 802.22 made it possible to optimize the use of the radio frequency spectrum, reduce the level of interference and increase the overall reliability of the system under conditions of high traffic.

One of the key advantages of the scientific solutions proposed in the article is the introduction of cognitive subsystems that analyze spectrum usage and automatically adapt system parameters for optimal use of available resources.

Compared to traditional telecommunication systems, CRS using IEEE standards demonstrate higher adaptability to changing communication conditions, which is critical for military and civilian applications.

The results proposed in the study allow to solve the problem of insufficient efficiency of the use of the radio frequency spectrum, to achieve the goal and tasks set in point 2.

Despite the advantages, the research has limitations related to the complexity of integrating cognitive technologies into existing (traditional) telecommunication infrastructures. In addition, the high cost of implementation can be a barrier to large-scale adoption.

Further development of this direction of research may relate to the analysis of cost-effective technologies of cognitive radio. As well as their adaptation to international standards. It is also possible to deepen the study of cyber security aspects of CRS to increase resistance to external threats, which is relevant for our country in the conditions of martial law and a difficult energy situation.

VII. CONCLUSIONS

The results of the study confirm that the goal of the article was achieved thanks to a comprehensive approach to the analysis of modern IEEE protocols and standards and the study of their impact on CRS. The goal was realized through the following scientific tasks.

1. With the help of detailed analysis and systematization of the existing subsystems of cognitive radio, it is determined how the optimization of their work can increase the efficiency of the use of the radio frequency spectrum. This included studying the mechanisms of adaptive frequency tuning, which allows the "smart radio" to reduce interference and optimize spectrum distribution depending on the radio environment. It has been proven that adaptive subsystems of cognitive analysis and decision-making allow radio systems to independently determine and switch to free frequencies, ensuring communication reliability.

2. The study of modern protocols and their specifications revealed key trends in the development of telecommunication technologies and their impact on CRS. It is well-founded that protocols significantly improve the compatibility of various systems and provide better resource management. This contributed to the creation of prototypes for more flexible and efficient systems capable of quickly adapting to changes in the conditions of the radio frequency environment, reducing signal loss and optimizing the use of the available spectrum.

3. Study of the influence of IEEE protocols on the radio frequency spectrum in highly loaded conditions. It confirmed that modern standards can significantly improve spectral efficiency. For this, it is necessary to implement adaptive implementation algorithms that dynamically adjust the distribution of frequencies and the use of transmitter power, as well as through the use of interference minimization technologies, which will ensure the stability and reliability of the telecommunications system.

AUTHOR CONTRIBUTIONS

O.K., V.L. – conceptualization, methodology, investigation; O.S. – writing-original draft preparation validation; O.V. – formal analysis, investigation, design of results; O.K., V.L., O.S. – writing-original draft preparation, visualization, supervision writing-review and editing.

COMPETING INTERESTS

The authors declare no conflict of interest.

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Аналіз протоколів безпроводового зв’язку для підвищення ефективності функціональності когнітивних телекомунікаційних мереж

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АНОТАЦІЯ В дослідженні були проаналізовані та систематизовані сучасні протоколи та їх специфікації. Виявлено переваги та недоліки, які необхідні для розширення можливостей застосування когнітивних радіосистем (CRS). Аналіз технічних характеристик CRS дозволив виявити основні фактори застою в різних технологічних можливостях. Доведено, що протоколи IEEE забезпечують критично важливу основу для стандартизації когнітивних радіосистем, сприяючи їх сумісності та ефективному використанню радіочастотного спектра. Обґрунтовано, що когнітивні радіосистеми включають підсистеми оптимізації для забезпечення надійного зв'язку. Зокрема, підсистема когнітивного аналізу є необхідною для ефективного моніторингу радіочастотного спектра, забезпечуючи адаптацію частоти у відповідь на зайнятість спектра. Підсистема когнітивного прийняття рішень забезпечує оптимальне використання ресурсів через раціональний розподіл частот і налаштування параметрів передачі. Адаптація та маршрутизація відіграють ключову роль у забезпеченні надійного обміну даними, а управління ресурсами та заходи безпеки зміцнюють цілісність і захист системи. Дослідження показало, що багаторівнева інтеграція підсистем відкриває нові можливості для підвищення ефективності використання радіочастотного спектра в умовах динамічних змін. Таким чином, впровадження сучасних протоколів та технологій у когнітивні радіосистеми є важливим кроком до створення більш гнучких та адаптивних мереж, здатних ефективно реагувати на змінні умови та вимоги користувачів. Аналіз, представлений у статті, демонструє необхідність та ефективність застосування інноваційних бездротових комунікаційних протоколів. Ці протоколи значно покращують пропускну здатність і спектральну ефективність, що, у свою чергу, сприяє оптимізації роботи мереж у «розумних» радіосистемах для різних застосувань – від військових до комерційних.

КЛЮЧОВІ СЛОВА Когнітивне радіо, протоколи IEEE, стандарти, специфікації, адаптивність.