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Research paper

Modern Technologies for Designing Communication Systems Using Ultra-Wideband Signals and The Main Areas of Development

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Abstract

The increasing demand for fast, reliable, and secure information exchange in modern telecommunications has led to a growing interest in ultra-wideband (UWB) signals. This study aims to explore the potential of UWB signals in modern radio communication systems, focusing on their integration into wireless networks of various scales and their effectiveness in ensuring stable communication under limited resources and high interference conditions. The research methodology involved a theoretical analysis and comparative review of existing approaches to the development and use of UWB-based systems. The study included a detailed examination of UWB characteristics and their comparison with other wireless communication methods such as Wi-Fi, Bluetooth, Zigbee, and 4G/5G networks. The results demonstrated that UWB signals can significantly improve the efficiency of information transmission in wireless networks, providing high-speed data transfer with minimal power consumption and high interference resistance. The study highlighted the importance of developing technologies to enhance the adaptability of UWB systems to different environments and operating conditions, thereby improving the productivity and energy efficiency of modern communication systems. In conclusion, UWB technologies show significant potential for integration into both large-scale and local wireless networks, offering innovative solutions for various communication challenges. Future research should focus on practical experiments and real-world measurements to further validate these findings, exploring adaptive power and frequency management techniques to ensure optimal performance and stability in conditions of limited resources.

Keywords: *Bandwidth; Data Transmission Optimisation; Energy Efficiency; Modulation; Radio and Communication Methods; Wireless Networks.*

1. Introduction

Modern telecommunications systems are increasingly focusing on technologies that can provide fast, reliable, and secure information exchange, especially in conditions of increased noise immunity. One of these solutions is ultra-wideband (UWB) signals, which radically change approaches to data transmission. A distinctive feature of UWB is its ability to use an extremely wide frequency band, which allows achieving high bandwidth without increasing the radiation power. This makes them inconspicuous for third-party systems, which ensures high secrecy of communication. The large spectrum width allows for high data transfer rates, and extremely low spectral density of signal power, which minimises the impact on other devices and systems.

However, despite the significant potential of ultra-wideband signals, their large-scale application faces several problems. One of the main ones is strict regulatory restrictions on radiation power, which affect the range and energy efficiency of systems. In terms of technical characteristics, UWB is defined by a spectrum width that exceeds 500 MHz or is more than half the central frequency of the signal. These parameters are regulated by international bodies such as the US Federal Communications Commission (FCC) (2025) and the European Telecommunications Standards Institute (ETSI) (2016). In addition, complex real-world environmental conditions, in particular, high levels of electromagnetic interference and multi-track effects, create significant difficulties for the stable operation of such systems. Another important challenge is the need to develop specialised algorithms and devices that ensure optimal UWB generation, transmission, and processing. This includes issues of signal synchronisation, adaptation of antenna systems, and the introduction of new modulation techniques to improve performance.

Analysis of communication system design technologies using UWB helps to close important gaps in understanding their effective application. This will contribute to the development of new methods for optimising signal generation and transmission that meet modern regulatory requirements and adapt to different environmental conditions. UWB analysis will identify promising areas for the development of communication technologies, such as building scalable wireless networks that meet the requirements for mobility, energy saving, and high device density. Thus, research in this area opens up opportunities for creating innovative systems that can function effectively in the highly dynamic environment of modern communications.

One of the key areas of development of ultra-wideband signals is their integration into modern communication systems, which requires improvement of signal generation, transmission, and processing technologies (Artemuk & Mykytyn, 2022). The study by Atanasov & Trifonov (2024) was devoted to the development of an interactive system, noting the possibility of integrating UWB into a wireless network, but the article lacked a comprehensive analysis of the impact of such algorithms on performance in multi-channel environments with high device density. The study by Vitanov & Nikolov (2024) considered methods for receiving UWB to improve the reliability of communication systems, noting the prospects of this technology, but the limitations of the experimental base did not allow for evaluating the effectiveness of the proposed methods in large-scale networks. Research by Khan et al. (2020) focused on optimising antenna systems for the use of UWB in modern communication systems, which allowed systems to adapt to changing conditions; however, it was noted that insufficient consideration of problems of compatibility of antenna systems with existing networks may limit their effectiveness in real-world conditions.

Another important area for development is the development of approaches to increase the stability of ultra-wideband communication systems to interference and adapt to high-density device conditions in modern networks. The study by Pérez-Solano et al. (2022) considered the implementation of spatiotemporal processing algorithms to reduce the impact of multi-path effects and improve the quality of signal reception, but it was noted that the lack of consideration of dynamic changes in the characteristics of the medium may limit the practical applicability of the results obtained. Yao et al. (2023) analysed methods for modulating UWB signals to ensure their compatibility with existing communication standards, but the study was limited to considering only static network models, without considering device mobility and the variable nature of traffic. The study by Jocqué et al. (2024) focused on the development of energy-efficient antenna systems for integrating UWB into local networks, but they did not pay enough attention to optimizing antenna designs to reduce side radiation, which is an important factor in densely populated environments.

Improving the efficiency of using ultra-wideband signals in multi-user communication systems also requires attention, where the issues of spectral resource optimisation and interference management remain open. The article by Luo et al. (2023) investigated the mechanisms of dynamic spectrum distribution to improve the performance of UWB systems in multichannel environments, which allowed for reducing the level of mutual interference between users, but with a limitation in the form of testing algorithms only with high device densities. Research by Fathy et al. (2020) focused on developing a low-power UWB transmitter that reduced power consumption, but at the same time, the study did not sufficiently consider the impact of various device operation scenarios on system performance. The study by Atanasova et al. (2022) was aimed at developing a UWB antenna for wearable devices of the Internet of Things, noting the effectiveness of this technology, but not enough attention was paid to the security of data transmission in such networks, which is critical for their practical implementation.

Current research on UWB signals lacks complete analysis and practical implementation in modern communication systems, especially in multi-channel setups with high device density and dynamic situations. Existing studies have examined UWB integration into wireless networks, energy-efficient antenna systems, and communication system reliability, but they often fail to address real-world application challenges. There is little research on how UWB algorithms affect system performance in complex, interference-prone situations and their flexibility to changing conditions and device mobility. In UWB-based networks, spectrum resource optimisation, interference management, and data transmission security are understudied. This gap highlights the need for more research to develop and test practical UWB system models that can operate effectively under regulatory constraints and high electromagnetic interference, ensuring stable and efficient communication in diverse and dynamic settings.

The purpose of this study was to explore the potential of using ultra-wideband signals in modern radio communication systems to ensure efficient and stable data transmission in various environments. Within the framework of the study, two main tasks were solved, which included the analysis of the possibilities of implementing UWB technology in wireless networks of various scales to optimise data transmission between distributed devices, and the analysis of radio communication technologies based on UWB signals, aimed at determining their effectiveness in ensuring stable communication in conditions of limited resources and high interference intensity.

2. Materials and Methods

The research methodology was based on a theoretical analysis and comparative review of existing approaches to the development and use of systems based on ultra-wideband technologies. To assess the effectiveness of UWB systems, methods of systematisation of technical characteristics were applied, and a comparative analysis of existing methods for their implementation. Special attention was paid to the analysis of mechanisms for increasing the stability of UWB communication in conditions of high interference and limited radio frequency resources, which was based on the study of adaptive signal processing methods.

The study examined ultra-wideband technologies and compared them to Wi-Fi, Bluetooth, Zigbee, and 4G/5G networks. By comparing the most common communication standards (IEEE 802.11 n, IEEE 802.11 ac, 3GPP), the effectiveness of these technologies was assessed. The key comparison criteria were bandwidth, energy efficiency, interference resistance, and signal temporal characteristics, including delay. Technology performance in the overloaded radio frequency spectrum was also assessed. Systematisation and generalisation of data and technological factors were utilised to assess UWB's advantages over other wireless standards for high-speed communication. The study and comparison of existing communication standards also examined mechanisms that efficiently transmit UWB signals with minimal energy loss and without affecting other radio frequency systems in the same frequency band. The spectrum expansion and pulsed radio communication techniques were examined. UWB signal features under multipath propagation situations, such as time-separated processing and coherent summing of reflected signals, were studied to improve communication accuracy and reliability. The capacity of UWB networks to adapt in real time was investigated utilising algorithms for dynamic signal parameter control, which ensures their steady functioning in a changing radio frequency environment.

The study also analysed the main problems faced by communication systems based on ultra-wideband signals. For this purpose, methods of critical analysis and systematisation of information about communication standards from open sources (US Federal Communications Commission 2025, European Telecommunications Standards Institute 2016) and comparative analysis of various approaches to the implementation of ultra-wideband signals were used. Special attention was paid to the analysis of UWB signal modulation technologies, including pulse modulation, to assess their effectiveness in conditions of limited energy resources and compliance with the requirements of modern wireless networks.

In high-noise and interference environments, spatial and temporal signal processing strategies were prioritised to ensure communication system stability. The study examined interference-compensating strategies. Adaptive signal processing was also researched to maintain system efficiency under fluctuating radio frequency conditions and strong interference. Least Mean Squares (LMS) and Recurrent Least Squares (RLS) adaptive filtering techniques were examined. To maximise environmental resistance and interference resistance, adaptive modulation approaches for automatic bandwidth adjustment, antenna amplification, and algorithm optimisation were investigated. For efficient operation, adaptive matching filters, multi-channel correlation analysers, and spectral-time converters were explored. Studying these devices and signal processing methods is crucial to understanding the technical aspects of UWB communication systems.

3. Results

a. Features of impulse information transmission via UWB

One of the unique properties of UWB is the use of ultrashort pulses to transmit information. Unlike narrow-band signals, which require multiple carrier-wave cycles to transmit an equivalent amount of data, ultra-wideband systems are able to encode information in each pulse, which significantly increases their efficiency. Ultrashort pulses in UWB systems typically range in duration from picoseconds to nanoseconds. The pulse can last 1-2 ns, which corresponds to a spectrum width of more than 500 MHz. This allows UWB systems to transmit data in each pulse, significantly increasing the efficiency and speed of information transmission compared to narrow-band signals. Narrow-band signals are characterised by pulses with a duration of microseconds or millimetres of a second. Narrow-band signals typically have a bandwidth in the kHz range of up to several tens of MHz. These signals require multiple carrier wave cycles to transmit the same amount of data as in UWB signals, since the information is encoded in specific frequencies or phases.
The use of ultrashort pulses can significantly reduce transmission time, which is very important in real-world conditions, for example, when operating in a noisy or loaded radio frequency environment (Moydunov et al. 2024). In addition, UWB systems demonstrate high resistance to interference due to the wide frequency band, which allows the signal to pass through noise sources without losing key information. They also have low radiation levels, making them suitable for use in densely populated areas or near sensitive equipment. Based on these properties, UWBs have become the basis for the development of such innovative areas as ultra-precise radar and high-speed wireless networks (Ghimire et al. 2021). At the global level, UWB technologies solve the problems of speed and reliability of data transmission and contribute to improving the overall efficiency of using the radio frequency spectrum (Bondarenko et al. 2013). Their integration into modern information systems allows creating solutions that combine security, stealth, and adaptability to a changing environment, thus providing the basis for new communication standards of the future.
UWB technology is increasingly integrated into a variety of modern consumer and industrial devices, showcasing its practical applications beyond theoretical analysis. In smartphones, UWB is used for precise spatial awareness, enabling features like Apple’s AirDrop directionality and device tracking with AirTags, as seen in the iPhone 11 and later models. In the automotive sector, UWB enhances security through digital keys, allowing keyless entry and ignition systems that are resistant to relay attacks, as demonstrated by BMW, Audi, and Hyundai. Furthermore, UWB is vital in smart home systems, where it powers precise indoor localization and context-aware automation, such as Apple’s HomeKit and motion-sensing devices developed by companies like NXP and Qorvo. These real-world applications exemplify UWB's role in enhancing security, efficiency, and precision, solidifying its potential for widespread use in high-tech environments and everyday devices.

b. Broadband communication systems: Comparative analysis and technical advantages of UWB

Communication systems that use ultra-wideband technologies are characterised by exceptional data transmission characteristics due to the large width of the frequency spectrum. This allows providing high-speed information exchange with low power consumption, which is one of the main advantages of UWB. An important role in understanding this process is played by Shannon’s theorem, which determines the maximum bandwidth of a communication channel, which depends on the width of its spectrum and the noise level (Abbas et al. 2025). The theorem states that the greater the width of the frequency range of a channel, the greater its bandwidth. For UWB, this means that increasing the spectrum width allows achieving significant data transfer rates – up to several gigabits per second. In addition, one of the main advantages of UWB technologies is high noise immunity to such types of interference as inter-signal interference, coherent and incoherent interference, and interference from other radio frequency systems operating in the same frequency range. Due to the uniform distribution of signal energy over a wide frequency spectrum, such systems effectively filter out interference. This allows compensating for the impact of interference even in conditions of low transmitter power. For example, correlation signal processing provides high data transmission accuracy, significantly exceeding the efficiency of conventional narrow-band systems.
The signal processing gain in UWB systems can reach 53 dB, which provides a significant advantage over other technologies, such as extended-spectrum systems that use fewer frequency bands (Luo et al. 2025). An important characteristic of such technologies is also their resistance to deliberate attacks aimed at disrupting the system. Due to the distributed structure of the spectrum, such signals are difficult to drown out even when using high-power interference generators. The economic and technical costs of organising such interference significantly exceed the effectiveness of such actions, which provides an additional advantage for ultra-wideband technologies. Table 1 shows the main technical characteristics of UWB compared to other communication technologies.

Table 1: UWB technical characteristics compared to conventional communication technology

Technology	Transmission banding	Bandwidth	Energy efficiency	Noise immunity
UWB (Ultra-Wideband)	3.1-10.6 GHz	Up to 1 Gbit/s (depending on conditions)	Low power (tens of MW)	High (resistance to interference and obstacles)
Wi-Fi (802.11n, 802.11ac)	2.4 GHz, 5 GHz, 6 GHz	Up to 9.6 Gbit/s (depending on the version)	Moderate (depends on the version)	Moderate (possible obstacles)
LTE (4G)	1.4-2.1 GHz	Up to 1 Gbit/s (in theory)	High (optimised for mobile networks)	High
5G	100 MHz – 1 GHz (for mmWave)	Up to 20 Gbit/s (in theory)	High (optimisation for a large number of users)	High
Bluetooth	2.4 GHz (Bluetooth Classic, BLE)	Up to 3 Mbps (Bluetooth 4.0), up to 2 Mbps (Bluetooth 5.0)	Very low (power up to 100 MW)	Moderate
Zigbee	2.4 GHz, 868 MHz, 915 MHz	Up to 250 kbit/s	Very low (about 1 MW)	High (due to low energy consumption)

Source: developed by the author.

c. Prospects for UWB application in networks of various scales

UWB communication systems are actively developing to meet the growing needs for fast, reliable, and secure data transmission. Due to their unique characteristics, UWBS are particularly useful in high-threat environments where conventional radio frequency technologies may be vulnerable. Military networks are one example of UWB applications. In such networks, the speed and reliability of data transmission between departments, and resistance to jamming and interference, are important. UWB has a low signal strength level, which ensures stealth communication, reducing the probability of signal detection and interception (Bondarenko & Galich, 2015). Due to the use of ultrashort pulses, UWB signals create minimal radio interference signatures, which makes them difficult to detect during monitoring. In addition, these technologies allow for quickly changing the transmission frequencies, which increases the resistance to jamming. Military units can use UWB to reliably exchange information, even in conditions of severe interference and with a high probability of enemy attacks on the communication system. In critical facilities such as nuclear power plants, refineries, and banking systems, UWB can be used for secure data exchange where the risk of signal interception is high. UWB technologies allow providing a high level of security, since signals are transmitted with a very low power level, which allows protecting important data from unauthorised access (Lazebnyi & Omelianets, 2024; Miroshnyk et al., 2023). In Bulgaria, where existing facilities with high security requirements, such as strategic infrastructure facilities and transport hubs, require reliable communication, UWB can become an effective tool for providing sustainable and secure communication channels. In the face of growing requirements for cybersecurity and protection of critical infrastructures, UWB can guarantee stable and secure data transmission, which is an important aspect for such facilities.
The main areas of use of UWB focus on the development and implementation of global and regional information transmission networks that have significant potential for integration into various fields of activity (Fig. 1).

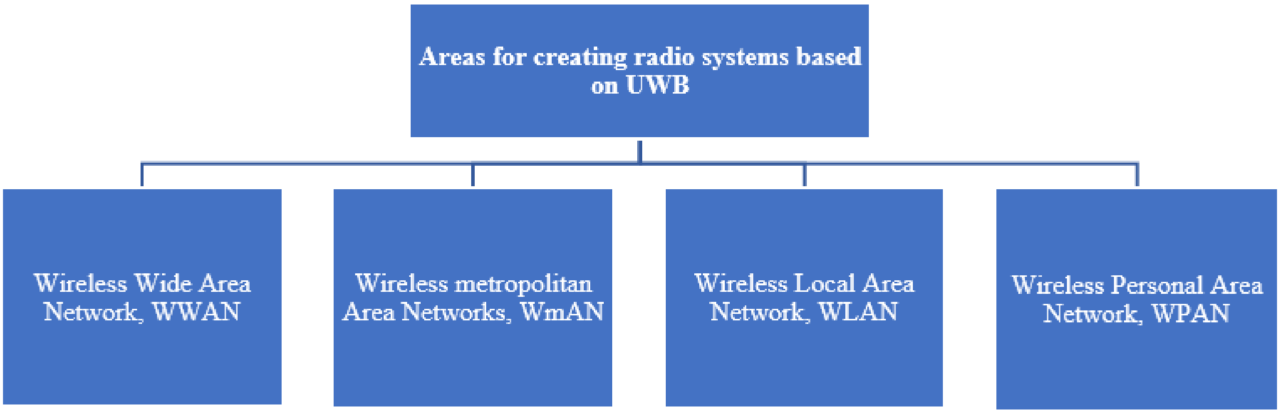

Fig. 1: Areas for creating radio systems based on ultra-wideband signals

Source: compiled by the author.

Global wireless wide area networks (WWAN) are sophisticated engineering solutions that use a wide range of technologies to ensure high-quality communication over long distances. One of the main technical features of WWAN is its ability to operate in frequency bands that provide an optimal ratio between signal transmission range and bandwidth. Usually, such systems use frequencies in the range of 700 MHz-2.6 GHz, which allows achieving stable coverage even in difficult conditions at up to 10 km (Švelec et al. 2020).
A technical feature of WWAN is the widespread use of modulation technologies, such as Orthogonal Frequency Division Multiplexing (OFDM). This technology allows dividing data transmission into several subchannels, which significantly increases the signal's resistance to interference and ensures efficient use of the frequency resource. In addition, WWAN supports dynamic adaptation of modulation depending on environmental conditions: in favourable conditions, more complex modulation schemes (256-QAM and others) are used to increase throughput, while in unfavourable conditions, simpler schemes are used to ensure connection stability. Another technical advantage of WWAN is the use of modern error correction algorithms, such as Turbo codes and LDPC (codes with a low density of parity checks). This allows for significantly reducing the number of errors during data transmission, even in conditions of high noise or interference, which is especially important for working over long distances. WWAN widely uses spectrum extension methods that increase their resistance to interference. Thus, frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS) technology distributes signal energy over a wider frequency range, which makes the signal less visible to third-party systems and increases protection against external interference (Nazir et al. 2021).
To ensure high bandwidth, WWAN uses multi-input Multiple Input Multiple Output (MIMO) systems, which allow simultaneous data transmission over multiple antennas. This significantly increases the efficiency of spectrum use and improves signal quality in multipath propagation conditions (for example, in cities with high building densities). Network integration technologies in WWAN also play an important role. They support various protocols, including LTE, 5G, etc., which allows combining different types of traffic, such as data transmission, voice communication, and video conferencing. This ensures high flexibility and scalability of the system. In practice, WWAN also uses modern methods of energy management (Wei & Geyi 2021). For example, beamforming technology allows focusing signal energy towards the receiver, which reduces energy loss and increases data transmission efficiency. Due to the combination of these technical features, WWAN is a universal solution for providing communication over large areas, providing stability, high data transfer rates, and resistance to interference in a wide variety of operating conditions.
Ultra-wideband technology has significant potential for integration into global long-range wireless networks, providing unique technical advantages in high-speed, energy-efficient, and noise-resistant communication (Azieva et al. 2021; Rexhepi 2023). Due to its ability to operate in the ultra-wide frequency range, UWB provides data transmission with a pulse width of less than 1 nanosecond, which allows achieving a throughput of up to 1 Gbit/s over short and medium distances. In the case of integration into WWAN, this provides a significant increase in the spectral efficiency of the network in areas with high traffic density, which allows optimising the use of the radio frequency spectrum and ensuring more efficient use of available frequency resources. UWB is also characterised by high time resolution, which provides extremely accurate positioning with an accuracy of several centimetres (Zhang et al. 2020).

In the context of WWAN, this can be useful for intelligent transport systems (ITS) and other high-precision applications, such as autonomous transport management or real-time route optimisation. In 5G networks, precise positioning also helps to distribute traffic more efficiently and optimise resource usage. The integration of UWB into WWAN opens new opportunities for creating high-speed, low-latency networks (Rubino et al. 2018; Ginters et al. 2018). The use of UWB allows significantly increasing the scalability of the network in conditions of dynamic traffic changes, providing stable coverage even in difficult conditions, such as tunnels or densely built-up areas, and creating universal adaptive systems for a wide variety of operating scenarios. Based on these technical advantages, UWB is an important element in the development of modern WWAN that meets the communication requirements of the future.

Regional wireless networks (WmAN) are elements of telecommunications infrastructure that provide data transmission within urban areas or industrial areas (Capasso et al. 2021; Bisenovna et al. 2024). Such networks usually operate within a radius of up to 1 km, which allows effective coverage of densely populated areas or specialised objects (Mubashar et al. 2021). One of their features is the use of unlicensed frequency bands, which reduces the cost of deploying infrastructure. To ensure the stability and efficiency of the WmAN signal, adaptive modulation methods are used, which allow adjusting the level of transmission complexity depending on environmental conditions, ensuring an optimal balance between data transfer rate and communication reliability.

The WMAN architecture provides two main approaches to network organisation: point-to-point (PtP) and point-to-multipoint (PtMP). In the first case, the network provides direct communication between two nodes, which is especially useful for high-speed backbone data lines. In the second approach, multiple devices can connect to a single node, which allows creating local zonal networks for data exchange within urban areas. OFDM technology is widely used to improve the efficiency of signal transmission, which provides signal separation into several subchannels. This avoids multipath signal propagation, which is a common problem in urban environments due to numerous signal reflections from buildings.

One of the important characteristics of WmAN is their low power consumption, which makes these networks energy efficient and suitable for long-term use. The transmitter signal strength usually does not exceed 100 MW, which reduces the risk of interference to other radio systems in the same frequency range. It also avoids the need to allocate additional frequency resources, making it easier to integrate the network into the existing infrastructure. Due to modern encryption methods such as WPA3 or AES-256, data transmission in WmAN remains secure even in difficult conditions. Signal protection is additionally provided using spectrum extension technologies, such as DSSS, which make signals less vulnerable to external interference. The bandwidth of modern WmAN can vary from 100 Mbit/s to 1 Gbit/s, depending on the equipment used and operating conditions (Anoop et al. 2021).

Wireless local area networks (WLAN) and wireless personal area networks (WPAN) also play an important role in communication technologies, ensuring high efficiency of data transmission within a limited space. WLANs are designed for communication between devices at 10 to 100 metres, making them an ideal choice for office space, industrial complexes, or residential buildings. WLAN is based on IEEE 802.11 standards, particularly the most common versions, such as 802.11n. These standards support data transfer rates from 54 Mbit/s to more than 1 Gbit/s, depending on the frequency range (2.4 GHz or 5 GHz) and the number of antennas in the devices. Encryption protocols such as WPA3 are widely used to ensure the security of data transmission in WLANs, which allow protecting the network from unauthorised access. In addition, quality of service (QoS) technologies help to prioritise traffic types, ensuring stable operation of applications that are sensitive to delays, such as IP telephony or video streaming. Due to their versatility and high speed, WLANs are actively used for automation of industrial processes, remote control of equipment, and data transmission to computer centres for their further analysis and storage (Koul et al. 2024).

The use of UWB technology in a WLAN can allow for significantly higher speeds and reliability in data transmission, especially in high bandwidth requirements such as video streaming, large amounts of information, or complex management teams in industrial or military applications (Dahan et al. 2025; Misura et al. 2021). Another important feature of this technology is its ability of this technology to work efficiently in interference conditions due to the technology of distributing signal energy over a wide frequency range. This allows UWB systems to work even in environments with a large amount of interference, especially in urban areas where there are numerous sources of radio interference. In terms of power consumption, UWB systems are very economical compared to conventional WLAN systems. Based on the use of short pulses of signals with very low power levels, UWB technologies can transmit data over long distances without significant energy costs (Allahverdiyev 2023; Niyazbekova et al. 2021). This is important for battery-powered devices, as it significantly extends their battery life. An additional advantage of UWB in a WLAN is that it supports a high level of accuracy in positioning and navigation within limited areas. Due to the high frequency and short pulses used in UWB, these systems can provide positioning accuracy up to 10 cm, which is critical for applications such as automation systems, robotic platforms, and for determining the exact location of objects in the Internet of Things (IoT) (Wang et al. 2021).

In turn, wireless personal area networks (WPAN) provide data transfer between devices located at up to 10 metres. WPANs are characterised by low power consumption, which is critical for mobile devices and wearable gadgets (Huseynzada et al. 2023). For comparison, WPAN technology such as Bluetooth can provide transfer speeds of up to 3 Mbit/s in its classic versions and up to 2 Mbit/s in the Bluetooth Low Energy (BLE) version, which is optimised for energy efficiency (Perez-Diaz-De-Cerio et al. 2021). ZigBee, in turn, has a lower transfer rate (up to 250 Kbit/s), but is characterised by high signal reliability, which makes it popular for automation of home systems and industrial applications (Shrestha & Shakya 2021). UWB technology, as one of the latest WPAN technologies, provides data transfer speeds of more than 100 Mbit/s, using the ultra-wideband frequency range, which significantly reduces the level of interference (Huang et al. 2021). A special feature of WPANs is their ability to support multiple connections between devices simultaneously, creating so-called "star" or "mesh" networks. Such networks are used to transfer personal data, for example, between a smartphone and peripherals, or to create interactive environments in smart homes. Due to their compact size and flexibility in deployment, WPANs are widely used in robotics, medical technology, and mobile solutions that require precision and fast information transfer (Doroshkevich et al. 2022; Sadigov et al. 2023).

The implementation cost of UWB technology tends to be higher than that of Wi-Fi or Bluetooth, primarily due to the more complex hardware and specialized chipsets required for UWB systems (Kerimkhulle et al. 2021). While Wi-Fi and Bluetooth rely on simpler, lower-frequency technologies with well-established infrastructure, UWB necessitates precise time-of-flight measurements and broader frequency bands, which require more sophisticated antennas and signal processing. However, UWB's high data rates, low power consumption, and resistance to interference can offset its higher initial costs in applications requiring high precision and reliability, such as in automotive security or high-speed indoor localization systems. As UWB technology becomes more widely adopted and production scales up, its cost may decrease, making it more competitive with Wi-Fi and Bluetooth in the long term.

An important characteristic of UWB systems is the extremely low level of signal power density (<-41.3 dBm/MHz), which makes it almost invisible to other technologies, reducing mutual interference and allowing UWB to be integrated into other protocols without compromising their performance (Polonelli et al. 2021). This approach minimises the risk of interference between different devices, even in environments with high concentrations of radio signals. In addition, due to the low level of radiation, UWB systems do not need to allocate a separate

frequency spectrum, which significantly reduces the cost of their implementation. This is especially important for organisations that operate in environments with limited resources or have strict regulatory restrictions on spectrum usage.
Radio communication systems based on UWB signal technology can be considered from several key aspects that determine their technical capabilities and scope (Fig. 2).

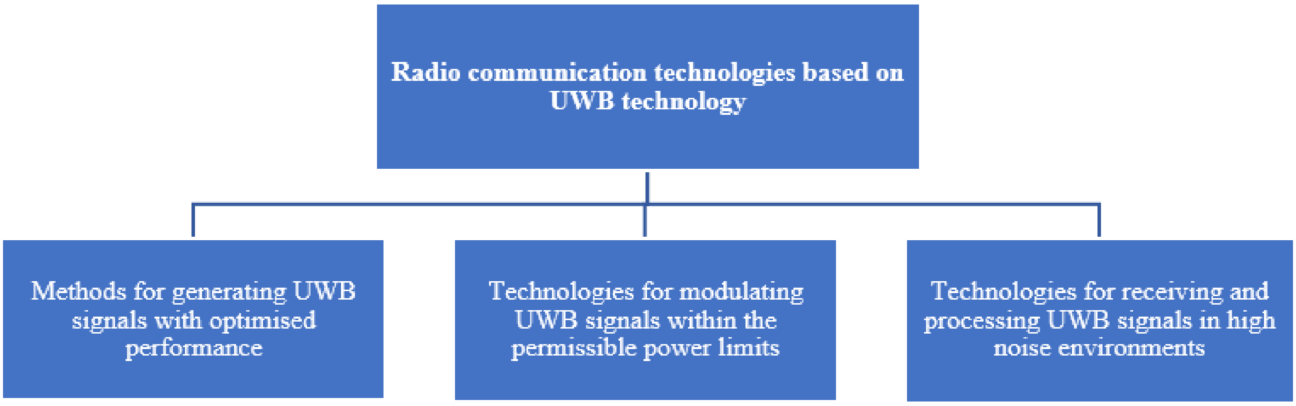

Fig. 2: Radio communication technologies based on the use of ultra-wideband signals

Source: compiled by the author.

d. Methods for generating, transmitting, and adaptively processing UWB signals under interference conditions

Methods for generating ultra-wideband signals with optimised time and frequency characteristics are the basis for ensuring efficient radio communication in difficult conditions. One of the main advantages of such signals is their ability to have a minimum pulse duration while maintaining a wide range of frequencies. This allows transmitting a large amount of information in a very short time, while minimising interference and saving energy in a compact time interval. Compared to conventional systems, UWB signals provide a high level of resistance to interference, as short pulses with a wide spectrum are less susceptible to attenuation in noise conditions, making them ideal for use in environments with high interference intensity.
To generate such signals, specialised antennas are used, which allow directing energy to a specific area and thus increasing the transmission efficiency (Cicchetti et al. 2022). Antennas that operate over a wide frequency range can concentrate power in each area, which increases the accuracy and range of communication (Bondarenko et al. 2010). They also optimise the pulse energy, maintaining the required power at low noise levels. The use of such antennas is important for achieving high efficiency of wireless communication channels, especially in difficult conditions, when it is necessary to maintain high accuracy of data transmission with limited resources.
To generate signals with maximum energy efficiency, the impulse radio UWB (IR-UWB) method can be used, where information is encoded in the form of short pulses lasting several nanoseconds. This allows concentrating signal energy in very short time intervals, reducing the average power consumption of devices. To further reduce energy losses, Adaptive Pulse Width Modulation is used, which dynamically adjusts the pulse duration depending on environmental conditions and the required bandwidth. This allows minimising energy consumption in favourable conditions, while maintaining high reliability of communication. Another method that contributes to energy efficiency is the use of time-based pulse compression. This approach consists of generating a broadband signal that is compressed over time on the receiving side using correlation receivers. This technology allows maintaining a high energy density of the signal and ensures its resistance to external noise and multipath propagation. In addition, UWB systems use spectral energy spreading, in which the signal energy is evenly distributed over a wide frequency range. This not only minimises the risk of mutual interference with other systems but also reduces the risk of signal interception, which is important for secure communication channels. Taken together, these UWB signal generation methods provide high-speed data transmission over long distances, while maintaining low power consumption and high interference resistance. This makes UWB technologies extremely effective in environments where accuracy, speed, and reliability are important, such as precision positioning systems, mobile wireless communications, and other critical applications where high levels of interference can significantly affect communication quality (Chehri & Mouftah, 2019).
To ensure efficient transmission of UWB signals within regulatory power limits, specialised antenna systems are used, which can be divided into two main groups, each of which has unique technical features (Table 2):

Table 2: Characteristics of specialized antenna systems for UWB signal transmission

Group	Description	Key Features
Adaptive Antennas with Adjustable Gain	These antennas adjust their characteristics depending on the signal frequency.	- Gradual increase in gain as frequency increases - Efficient use of energy resources - Minimizes signal loss by adapting to the transmission environment - Ensures stable operation in difficult conditions - Maximizes compatibility with other transmission system elements
Gratings with Independent Frequency Elements	These systems work based on high-speed control of elements for accurate signal direction.	- Constant orientation of the main radiation beam over the entire frequency range - Minimizes side radiation - Achieves high signal quality and transmission efficiency - High tuning speed avoids losses in phase characteristics - Critical for operation in conditions of limited power

Source: based on Shrome et al. (2021), Ghimire et al. (2021).

The energy efficiency of both systems depends on the parameters of their elements and the signal capabilities. For adaptive antennas, it is important that they can increase the transmission range due to optimal gain, which varies depending on the signal frequency. Antenna arrays achieve their results due to the precise coordination of spatial and temporal characteristics of signals, which avoids exceeding regulatory limits. Thus, both groups of antenna systems ensure optimal operation of UWB communication, creating a balance between high transmission rates and compliance with standards for radiated power. They allow significantly expanding the capabilities of systems without the risk of interference for other users of the frequency spectrum.

Ultra-wideband signal reception and processing technologies have become widely used due to their ability to function effectively even in difficult conditions where the level of electromagnetic interference is high. This is achieved through a combination of adaptive algorithms, state-of-the-art devices, and innovative processing methods that ensure stable communication and high data transmission accuracy. One of the key elements of this technology is the spatial and temporal synchronisation of signals. UWB receivers integrate spatial and temporal aspects into a single approach that determines the direction of signal arrival, compensates for the impact of reflections and delays, and adaptively adjusts the parameters of the receiving antenna in accordance with changes in the environment (Langella et al. 2016). This approach allows for minimising signal loss and improving transmission quality even in the most difficult conditions.

UWB systems use specially designed antiphase components that are added to the signal to neutralise interference (Morkun et al. 2023). For this purpose, a variety of technical solutions are used, such as delay systems with dispersion properties, configurable narrow-band filters to eliminate unwanted frequencies, and components for signal phase inversion. Based on these technologies, the signal-to-noise ratio at the output is significantly increased, which ensures reliable operation even in conditions of strong interference. Adaptability is another important characteristic of UWB systems. Receiving devices automatically adjust their parameters depending on environmental conditions. This includes changing the bandwidth, amplifying antennas, and configuring processing algorithms to maintain stable communication quality under variable conditions, such as moving objects or unexpected sources of interference (Kalde et al. 2024).

Time-separated processing is used to compensate for multi-channel signal propagation, which is an important problem in wireless systems. In multi-channel propagation, the signal reaches the receiver through several different paths, which leads to interference between the signals, reducing the quality of communication. Time-separated processing allows analysing the reflected signals, comparing them with the primary signal, and thus adjusting the delays between signals. This allows for minimising interference and improving the accuracy of data recovery. It considers parameters such as delay between signals and time sampling, which allows achieving high accuracy even in conditions of strong multiplexing. A coherent summation of reflected signals can be used to correct the phases between reflected signals. This allows for reducing the effects of multi-channel propagation and improving transmission accuracy. Coherent summation provides better phase synchronisation of received signals, which reduces the impact of interference and improves the signal-to-noise ratio (SNR). In addition, coherent summation can significantly reduce the Bit Error rate (BER) compared to conventional methods without coherent signal processing (Kakhki et al. 2023).

Algorithms for dynamically regulating signal parameters are an important tool for adapting the system to changes in the radio frequency environment (Andriievskyi et al. 2024; Kravtsova & Ziuhan 2024). Adaptive bandwidth (BW) adjustment allows the system to change its bandwidth depending on the level of interference and environmental conditions. This allows optimising the use of the spectrum and maintaining high communication quality even in difficult conditions. In addition, dynamic adjustment can include signal strength adjustments and antenna settings to maximise system efficiency in a real-world environment. Such algorithms ensure stable operation of the system, helping to adapt to constantly changing radio frequency environment conditions and ensuring high reliability and quality of communication. In turn, adaptive modulation methods allow changing the modulation scheme in real time to increase energy efficiency and reduce transmission errors.

When the signal strength in the channel decreases due to interference or long distances, the system can automatically switch to a more stable but less efficient modulation scheme, reducing the transmission rate but maintaining reliability. An important characteristic of adaptive modulation is the ability to automatically adjust the data transfer rate depending on changes in interference, which allows maintaining high throughput without significant losses (Xiang et al. 2024). Adaptive bandwidth adjustment is an important element for optimising the operation of UWB systems in a variable radio frequency environment. The bandwidth determines how much data can be transmitted per unit of time. In the event of large interference or channel interference, the system can automatically reduce the bandwidth to reduce interference and maintain communication stability. This allows increasing the reliability of transmission, reducing the likelihood of data loss. Otherwise, in a clean channel environment, the bandwidth can be increased to achieve maximum throughput. In turn, adaptive antenna gain control allows changing the gain level depending on the signal received from the antennas. This adaptation helps maintain a high level of communication reliability, even in an unstable environment.

Adaptive algorithms such as LMS and RLS can also be used to improve signal quality by adjusting real-time filters to compensate for interference and interference in the communication channel. Adaptive filtering by the LMS method is one of the most common approaches for real-time signal processing. This method is based on minimising the square error between the input signal and the filtered signal, which reduces the impact of interference. The LMS method works by gradually adjusting the filter parameters at each step, which allows effective adapting the filter to changing environmental conditions. One of the main characteristics of the LMS method is the speed of its learning, determined by the step of adaptation. For example, in conditions where interference changes rapidly, the learning step can be increased for faster adaptation, which reduces the BER by 30-40% compared to methods without adaptive signal processing. The LMS method may have performance limitations for very rapid interference changes, so more complex algorithms are used in such cases. Adaptive filtering by the RLS method is a more complex and accurate method compared to LMS, since it uses recursive optimization of filters based on previous signal values. RLS allows for faster adaptation compared to LMS, in particular, with stable adaptation of filters to compensate for variable interference, in particular, in frequency channels with high noise levels. The main advantage of the RLS method is its ability to quickly respond to changes in environmental conditions, in particular, to non-stationary interference, reducing the SNR by 10-15 dB compared to methods that do not use adaptive filtering (Piccinni et al. 2020).

Advanced devices such as adaptive matching filters, multi-channel correlation analysers, and spectral-time converters are used to process UWB signals. Adaptive matching filters are adjusted to the selected signal characteristics, which ensures their flexibility for different use cases. Multi-channel correlation analysers are capable of handling a large number of discrete signal samples over very short time intervals, making them effective even for ultrashort pulses of up to a nanosecond in duration. Spectral-time converters allow studying signals simultaneously in the time and frequency planes, detecting the smallest changes in the spectral structure. In urban environments where signal reflections from buildings and other objects play a significant role, UWB systems are particularly effective. They can process signals based on their multi-channel components, which often cause distortion. Due to the accurate analysis of time-frequency parameters, it is possible to maintain the correctness of the signal even in such difficult situations.

All this makes UWB signal reception and processing technologies a powerful tool for ensuring reliable communication in conditions of high levels of interference. Due to the integration of adaptive algorithms, state-of-the-art devices, and innovative processing methods, they open up new opportunities for working in complex environments, ensuring high-quality communication and data transmission.

4. Discussion

The results of the study demonstrated a significant potential of ultra-wideband signals for integration into modern radio communication systems. Due to their unique characteristics, such as high data transfer rate, interference resistance, and minimal power consumption, UWB signals can significantly improve the efficiency of information transmission in wireless networks. This creates opportunities for more efficient interaction between distributed devices, which is especially important for the introduction of innovative technologies. The use of UWB allows solving current problems of modern radio communications to ensure the reliability of data transmission in conditions of high interference levels and to optimise the use of energy resources. The results of the study also highlight the importance of developing technologies to improve the adaptability of UWB systems to different environments and operating conditions. This opens up prospects for further improvement of modern communication systems, such as Wireless Sensor Networks, IoT devices, 5G networks, industrial communication setups, medical devices, and autonomous vehicles, aimed at enhancing their productivity and energy efficiency. These advancements are expected to boost data transfer rates, reduce latency, and increase resistance to interference, thereby driving innovation and efficiency across various sectors. The study by Qian et al. (2022) also analysed the possibilities of using ultra-wideband signals in wireless communication systems, noting the effectiveness of UWB technology, but without considering complex conditions such as interference or obstacles, which limited the practical applicability of the results obtained.

The study by Taki & Abou-Rjeily (2022) was aimed at investigating the effect of various modulation parameters of UWB signals on data transmission efficiency, emphasising their importance for efficient operation of the system, but without considering the adaptability of these technologies to conditions of high interference density, which is important for real-world applications. Hechenberger et al. (2021) focused on evaluating the efficiency of UWB systems, helping to evaluate their performance in conditions of high interference and multichannel signal propagation, but without considering the effect of changes in signal strength in real networks, which is crucial for achieving stable communication in complex environments. Thus, in comparison with these articles, the results of this study provide a more comprehensive picture of the application of UWB in modern communication systems, complementing existing research by analysing both signal generation and processing technologies, and adapting systems to difficult operating conditions, which allows ensuring high efficiency of wireless networks in real conditions.

The results of the study showed that ultra-wideband signals have important potential for efficient operation of large wireless networks, such as WmAN and WWAN. Due to their ability to cover a wide range of frequencies, these technologies can provide high-speed data transmission even over long distances. They provide stable communication by reducing the impact of electromagnetic interference, which is an important problem for large networks with numerous connected devices. UWB's expanded ability to adapt to different environmental conditions also opens new opportunities for using these technologies in large-scale networks, providing stable communication even in difficult conditions, such as high interference levels or multi-channel signal components in urban areas. This increases the overall efficiency of such networks and allows the creation of innovative solutions for large communication systems that must be resistant to changes in the environment, supporting continuous data transmission over long distances with minimal energy costs. During the study by Hanzel & Grzechca (2021) also investigated the use of UWB technologies in the context of large wireless networks to improve security in smart cities, but the results are limited only to theoretical models without considering real-world conditions. Flueratoru et al. (2020) focused on the analysis of UWB energy efficiency, noting the prospects of this technology, but without considering the impact of various types of interference on the transmission rate in conditions of high density of connected devices. The study by Matta et al. (2023) investigated approaches to using UWB to improve bandwidth in large networks, but without considering the possibility of integration with other types of communication networks, such as 5G. Compared to the results of this study, this study examines a wider range of opportunities for integrating UWB technologies into large networks, including real-world interference conditions, energy efficiency, and signal optimisation, which helps to better predict the performance of such networks in the future.

In addition, because of the study, the significant potential of ultra-wideband signals in local wireless networks (WLAN, WPAN) was emphasised. Local area networks are traditionally used to connect devices in limited areas, such as homes, offices, or small businesses, where the need for high-speed data transmission and low power consumption is critical. The use of UWB in these networks can significantly improve the performance of such systems. Since UWB signals can provide high data transfer rates with minimal power consumption, this contributes to the creation of more efficient solutions for use in resource-constrained environments, such as short-range and limited device power. In addition, the ability of UWB to operate on a wide range of frequencies reduces the likelihood of interference from other RF devices, which is important in multi-frequency environments such as urban environments or environments with many wireless devices. Mahmood et al. (2020) investigated the potential of UWB in local area networks, noting that it can provide high data transfer rates with minimal energy consumption, but the results did not consider the effect of external interference on signal stability in real conditions.

The study by Shah et al. (2021) focused on reducing delays in data transmission in networks using UWB, which proved important for ensuring high-quality communication under heavy loads; however, the study did not analyze the power consumption at such intensive transmission. The study by Meng et al. (2022) considered the integration of UWB into an existing navigation network, which helped to improve the quality of navigation even in difficult conditions, but without considering the impact of spectrum overflow. Although the results of this study support the conclusions of these studies regarding the significant potential of UWB in local networks, this study provides a more in-depth analysis for both global and local networks. This study also focused on the details of signal modulation, reception, and processing technologies that can improve the efficiency of UWB systems in difficult conditions, which have not been sufficiently considered in these studies.

Research on UWB-based radio communication technologies has shown significant potential to improve the efficiency and reliability of wireless communications. It was found that optimised UWB signal generation methods provide high data transfer rates with minimal power consumption, which is crucial for applications with limited resources. Signal modulation technologies operating within acceptable capacities allow maintaining communication stability even in conditions of a saturated radio frequency spectrum, which is important for large and local wireless networks. In addition, signal reception and processing methods under high interference conditions help to increase the stability of systems to interference, which helps to function effectively in complex radio conditions with high interference intensity. This opens new opportunities for the development of reliable wireless communications in various areas, from home devices to large-scale infrastructure solutions. The study by Wei et al. (2022) considered methods for generating UWB signals with optimised time-frequency characteristics, which helped to increase the efficiency of radio communication systems, but the study did not consider the influence of various environments on these characteristics, which is an important factor for the practical implementation of technologies in real conditions.

In addition to the advancements in existing communication technologies, the exploration of 6G networks, anticipated for implementation around 2028–2030, presents a promising frontier for ultra-wideband (UWB) applications. While 5G networks have already begun to transform communication with higher data rates and lower latency, 6G is expected to further revolutionize wireless communication by integrating advanced technologies such as terahertz communication, AI-driven network optimization, and ubiquitous connectivity. UWB technology, with its high data transfer rates and minimal power consumption, is poised to play a crucial role in the development of 6G by providing the necessary bandwidth and efficiency. The integration of UWB in 6G could enhance applications such as real-time holographic communication, advanced IoT ecosystems, and seamless connectivity in densely populated urban areas. This synergy between UWB and 6G could lead to unprecedented improvements in network performance, reliability, and user experience, setting new benchmarks for future communication systems.

The study by Sharma et al. (2021) considered technologies for modulating UWB signals within acceptable capacities, which ensured communication stability at low power levels, reducing power consumption, but without considering the influence of many interferences, which is a critical aspect for operation in complex radio environments. Kocur et al. (2021) analysed the methods of receiving and processing UWB signals under high interference conditions, which significantly improved the reliability and accuracy of data transmission in complex radio environments, but it was noted that the use of the latest approaches to adaptive frequency and power control is not necessary to ensure energy efficiency and improve communication stability. The results of these studies show significant advances in improving UWB technologies, while the results of this study indicate the importance of an integrated approach to the study of various aspects of these technologies, which allows for more accurate assessment of their potential in different environments and networks.

The results of this investigation and the referenced studies showed that ultra-wideband signal technology has great potential in modern radio communication systems. Wireless networks of various scales will benefit from their high data transfer rates, energy efficiency, and interference resistance. IoT, next-generation mobile networks, and local and big networks can benefit from the findings. This will enable more reliable and adaptable communication systems that can adapt to modern requirements and working environments, advancing communication technologies and their integration into numerous industries.

5. Conclusion

As a result of this study, the possibilities of using ultra-wideband signals (UWB) in modern radio communication systems were investigated. In particular, it was found that such technologies have significant potential in wireless networks, in particular, in large (WMAN, WWAN) and local area networks (WLAN, WPAN). This allows efficient data transfer between distributed devices, which is the basis for creating innovative communication systems such as IoT or next-generation mobile networks.

It was found that the basis for effective operation of UWB radio communication systems is the use of technologies that provide signal generation with clear characteristics, and optimization of signal transmission and processing processes that meet the requirements for the power level and consider environmental conditions. As a result of the analysis of technologies for generating and processing ultra-wideband signals, several aspects were identified that determine their effectiveness in difficult radio communication conditions. In particular, the main advantage of UWB signals is their ability to provide high-speed data transmission over long distances with minimal power consumption and high resistance to interference. This is achieved due to short pulses covering a wide range of frequencies, which allows maintaining high transmission accuracy even in conditions of high interference intensity. An important role in improving the efficiency of UWB systems is played by specialised antennas that can adapt their characteristics depending on the signal frequency, and short-term modulation technologies that allow adjusting the time and frequency parameters of the signal to optimise its characteristics. This allows for reducing energy losses and ensuring stable signal transmission even in conditions of limited resources. Antenna systems with adjustable gain and high-speed grilles allow efficient signal direction and minimise side radiation, which is especially important in conditions of limited space and high interference density. Another important aspect is the introduction of adaptive algorithms for signal reception and processing, which allows UWB systems to function effectively even in complex environments with high levels of electromagnetic interference.

Further research may focus on developing and testing practical models of UWB systems in real-world urban environments, considering the impact of interference, multi-track components, and various types of interference. It is also important to explore adaptive power and frequency management techniques to improve the energy efficiency and stability of communication in conditions of limited resources, which will ensure optimal performance and stability of systems with minimal energy consumption, contributing to the development of high-speed wireless communications and improving the quality of communication in conditions of high noise sensitivity.

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