№ 2(55) 2025

МЕТОДИ ТА ПРИЛАДИ КОНТРОЛЮ ЯКОСТІ

ISSN 1993-9981 print
ISSN 2415-3575 online

https://mpky.nung.edu.ua

Методи і засоби неруйнівного контролю

Прийнято 17.12.2025. Прорецензовано 23.12.2025. Опубліковано 29.12.2025.

UDK 620.1 DOI: 10.31471/1993-9981-2025-2(55)-41-49

WIRELESS INFORMATION TRANSMISSION TECHNOLOGIES IN AUTOMATED NON-DESTRUCTIVE TESTING SYSTEMS

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Запропоноване посилання: Nechai, I. B., Lutsak, D. L., Demidov, I. A., Bilyuk, I. S. & Zivenko, O. V. (2025). Wireless information transmission technologies in automated non-destructive testing systems. Методи та прилади контролю якості, 2(55), 41-49. doi: 10.31471/1993-9981-2025-2(55)-41-49

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Abstract. The article presents an analysis of modern wireless information transmission technologies and their application in automated non-destructive testing (NDT) systems. The main wireless protocols used in industry are considered, in particular Bluetooth, Wi-Fi, UWB, GPRS, as well as the latest solutions for distributed sensor networks of the new generation. Each technology is evaluated according to the criteria of range, data transfer rate, power consumption and resistance to interference, which allows determining their feasibility for various types of non-destructive testing, including monitoring the condition of metal structures, pipelines, tanks, aviation and shipbuilding elements, as well as equipment of nuclear and chemical enterprises. Considerable attention is paid to wireless network topologies, among which point-to- point, star, multi-cell (mesh) and ring are considered. A comparison of their characteristics in terms of reliability, scalability, configuration complexity and integration efficiency into industrial facilities is presented. In the context of NDT, topologies determine not only the efficiency of data transmission, but also the ability of the network to provide fault tolerance and continuous monitoring of critical objects, where loss of communication even for a short time can lead to unreliable assessment of the technical condition. The article shows that the correct combination of modern technologies and appropriate topology allows you to create scalable, reliable and energy-efficient NDT systems that can provide timely detection of defects, predict the condition of materials and structures, and increase the safety of production processes. In addition, the use of wireless networks simplifies the organization of remote monitoring, reduces the need for physical access to objects and allows you to integrate data from various sources into diagnostic systems.

Keywords: non-destructive testing, star topology, wireless data transmission, parameter measurement, data acquisition system.

Introduction

The development of modern industrial sectors, such as aviation, chemical, oil and gas processing, coal and metallurgy, as well as the intensive improvement of vehicles, is accompanied by a constant increase in the technical complexity of production processes [1]. With the emergence of new technologies related to the processing of gases, liquids and solids in difficult and extreme conditions (high temperatures, pressure, humidity, aggressive environments, radiation exposure), there is a need to improve safety control systems and equipment reliability [2].

Modern industry requires not only the creation of new technological means for monitoring and controlling processes, but also the development of high-precision analytical equipment, modern sensors and materials that have unique physicochemical properties, resistance to extreme conditions and versatility of application [3]. This need is especially acute in areas of increased risk: during the operation of large-capacity aircraft, supertankers, main oil and gas pipelines (including those located on the seabed), nuclear power plants, as well as other critical infrastructure facilities [4]. The probability of man-made accidents at such facilities is largely determined by the level of development and efficiency of non-destructive testing (NDT) systems [5].

That is why one of the key tasks of modern science and technology is to create a perfect, technologically diverse complex of NDT technologies and tools based on the achievements of physics, chemistry, materials science, electronics and information technologies [6]. The development of such systems ensures timely detection of defects, prediction of the state of materials and structures, and also guarantees safe and efficient operation of complex technical systems in all industries [7].

Given the increasing requirements for the speed of data acquisition and analysis, the use of wireless technologies for transmitting information in NDT systems is becoming increasingly relevant. The use of wireless communication channels in non-destructive testing opens up the possibility of creating mobile, autonomous and distributed monitoring systems capable of transmitting measurement results in real time [8]. This is especially important for monitoring objects located in hard-to-reach or dangerous areas, for example, oil and gas pipelines, tanks, nuclear power units, aviation and shipbuilding structures, where laying wired connections is technically difficult or economically unjustified.

Thanks to the development of modern wireless technologies, such as Wi-Fi, Bluetooth, ZigBee, LoRaWAN, 5G, NB-IoT, the transmission of large amounts of data with high speed, low latency and stable communication quality is ensured even in difficult operating conditions. This allows integrating NK sensors into intelligent technical condition monitoring systems, creating sensor networks (Wireless Sensor Networks, WSN) and implementing the concept of the Internet of Things (IoT) in the field of quality control and safety [7].

The use of wireless technologies helps to increase the efficiency of data processing, simplifies the organization of remote monitoring and reduces the need for physical access of personnel to controlled objects, which increases the safety of service. In addition, it provides the possibility of centralized collection, storage and analysis of information, which is crucial in building intelligent systems for diagnostics and forecasting the condition of equipment.

The aim of the work is to identify key technical means of automated information exchange between measurement objects.

Types of wireless sensor network technologies

Currently, the most common wireless data transmission technologies in the industrial environment are Bluetooth, Wi-Fi, WiMAX, GPRS, etc. [9]. Typically, such systems are used in separate areas of production to perform highly specialized tasks - collecting telemetry, transmitting data from sensors, monitoring process parameters, etc. [10]. Fig. 1 presents possible areas of application of such technologies.

However, with the acceleration of the development of technologies for the extraction and processing of raw materials, there is a need for a wider implementation of wireless networks in automated control systems, in particular in the field of non-destructive testing [11]. This opens up opportunities for optimizing technological processes, increasing the efficiency of decision-making, and ensuring stable product quality at all stages of production.

Bluetooth is an industry specification for short-range wireless personal area networks. It enables data exchange between devices over a publicly available and free radio frequency range of up to 50 m (the actual distance

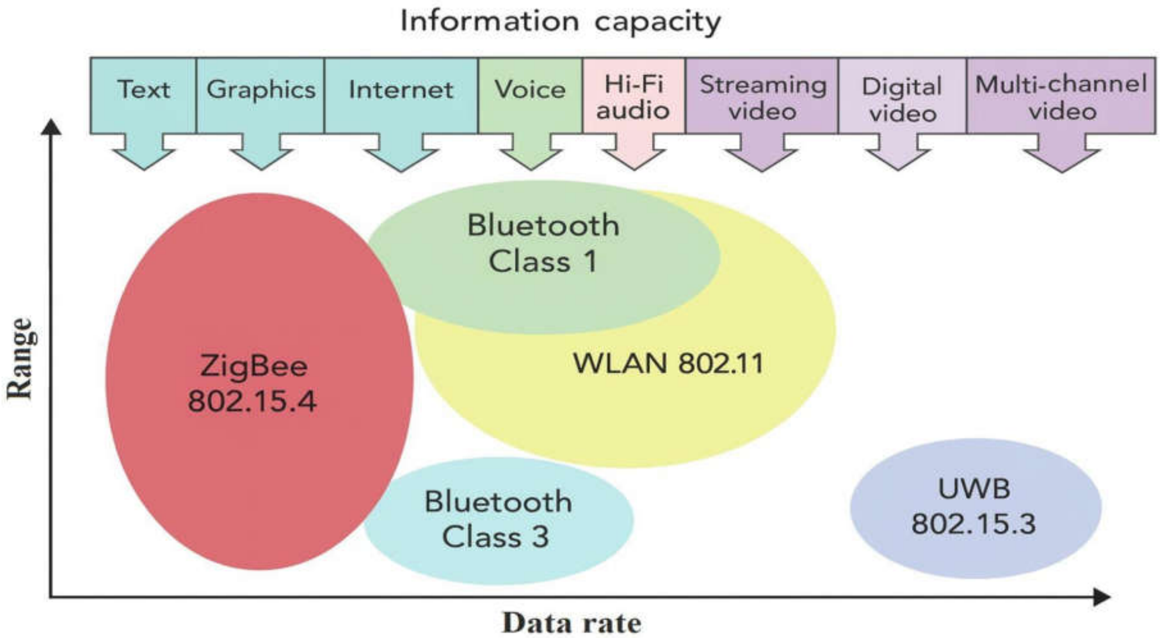

Figure 1 – Classification of some wireless standards

depends on physical obstacles in the signal path). Bluetooth operates in the ISM (Industry, Science and Medicine) band of 2.4–2.4835 GHz, which is unlicensed and widely used in everyday life and [12]. Bluetooth uses the FHSS (Frequency Hopping Spread Spectrum) method, which is a hopping modification of the carrier frequency.

Typical data transfer rate is 1 Mbps, packet size is 8–27 bytes. Due to its low power consumption, Bluetooth is used for sensors, portable NDT devices, and mobile measurement systems.

Wi-Fi is a wireless local area network technology that is widely used in automated monitoring systems. Although it is not yet supported by many manufacturers in the industrial market, there are specialized solutions, in particular from Siemens Automation & Drives, that operate according to the IEEE 802.11g standard in the 2.4 GHz band. Wi-Fi is capable of providing speeds of up to 54 Mbps at distances of up to 300 m, although the actual range depends significantly on interference and obstacles.

The technology is developing rapidly. One of the promising directions has been the implementation of the IEEE 802.22 standard, which allows: to transmit data at speeds up to 22 Mbps, to operate at distances up to 100 km from the transmitter. This opens up opportunities for using Wi-Fi in large, geographically distributed control systems.

WiMAX is a telecommunications technology for providing broadband wireless communication over long distances. It is based on the IEEE 802.16 (Wireless MAN) standard and includes: base stations, subscriber stations, network equipment for their connection to the provider and the Internet. The 1.5–11 GHz range is used for station interaction.

Under favorable conditions, the speed can reach 70 Mbps, and there is no need for direct visibility between the station and the receiver. The coverage area is several tens of kilometers, but for operation it is necessary to obtain a license to use the appropriate frequencies. WiMAX is suitable for creating regional or inter-site monitoring systems in the NDT.

GPRS is a superstructure of GSM mobile communication technology, which provides packet data transmission. The principle of operation of GPRS resembles the operation of the Internet: data is divided into packets, transmitted along independent routes and collected in receiving devices. When establishing a connection, each device receives a unique address, which actually makes it an analogue of a server. Advantages of GPRS: transparent work with the TCP/IP protocol, the ability to integrate into the Internet, coverage of large mobile communication areas. The maximum speed is up to 171.2 Kbit/s, and the operating area is limited to the coverage of the mobile operator. These technologies are summarized in Table 1.

New wireless technologies and their importance for automated non-destructive testing systems. The development of industry and the increasing requirements for monitoring efficiency have led to the emergence of new wireless solutions capable of operating in extreme conditions and transmitting large amounts of data with high accuracy. Modern wireless technologies that are actively implemented in automated non-destructive testing systems include LoRaWAN, NB-IoT, 5G and new generation UWB. LoRaWAN provides data transmission over a distance of up to 15–20 km with very low power consumption, which makes it ideal for distributed sensor networks of NDT over large areas. NB-IoT (Narrowband IoT) uses the infrastructure of cellular networks and supports thousands of sensors on a single base station, ensuring reliable operation in rooms, mines and underground tunnels. 5G is characterized by ultra-low latency – less than 1 ms, high bandwidth up to gigabits per second and support for networks with very high sensor density (mMTC), which makes it a promising solution for real-time, in particular for monitoring aerospace or nuclear facilities. The new generation UWB provides high positioning accuracy up to 10 cm and immunity to interference, which allows it to be used for zonal monitoring of structures and control of equipment movement.

Table 1 – Comparison of Wireless Communication Standards

Standard	802.15.4 ZigBee™			802.15.1 Bluetooth	802.15.3a* UWB	802.11b Wi-Fi
Applications	Monitoring, control, sensor networks, home/industrial automation			Voice, data, cablereplacement	Streaming media, audio/video system cable replacement	Data, video, LAN
Advantages	Price, energy savings, network size, less crowded bands		Price, energy savings, network size, global range	Price, energy - savings, voice transmission, frequency hopping	High speed, energy saving	Speed, flexibility
Frequency, GHz	0.868	0.915	2.4	2.4	3.1 - 10.6	2.4
Max speed	20 kbps	40 kbps	250 kbps	1 Mbps	110 Mbps (Yum), 200 Mbit/s (4 m) (additional 480 Mbit/s)	11 Mbps
Output power (nom.), dBm	0			0 (class 3) 4 (class 2) 20 (class 1)	<20 (110Mbps) <24 (200Mbps)	20
Range, m	10-100			10 (class 3) 100 (class 1)	10 (110Mbps) 4 (200Mbps)	100
Sensitivity (specification, dBm)	92		-85	-70	-	-76
Stack size, KB	4-32			>250	-	> 1000
Battery life, days	100- 1000+			1-7	theoretically more than 1000	0.5-5
Network size	65536 (16-bit addresses), 264 (64-bit addresses)			master +7	up to 127 per host	32

Types of sensor network topologies

The basis of the functioning of wireless networks is their topology and architecture, which determine the interaction between sensors, transmitters, receivers and computing modules. In addition, important characteristics of such networks are speed, power consumption, reliability, immunity to interference and security of transmitted data – especially in conditions of industrial facilities with increased danger.

When designing a wireless network, it is necessary to take into account the volume of data generated by sensors, the number and types of nodes, the scalability of the system, as well as the requirements for the speed and stability of information transmission. An important factor is the choice of the optimal topology, which determines the structure of the interconnections between the elements of the system. In the context of wireless, the topology describes not cable connections, but a logical scheme for organizing data flows – for example, a star, mesh, tree or hybrid structure.

Properly selected wireless network topology and architecture allow for the creation of highly efficient, mobile, and fault- tolerant NDT systems capable of providing continuous NDT in real time**.**

One of the simplest and most common structures for organizing wireless networks in non-destructive testing systems is the Point-to- Point topology. In this configuration, the network consists of only two devices, between which a direct data exchange channel is established. Both nodes, as a rule, are equal, which makes the network peer-to-peer and simplifies the process of information exchange.

The point-to-point topology is typical for many wireless technologies that are widely used in industrial monitoring systems. Among them: Bluetooth, ANT, RFID, RuBee, PDC, Wi-Fi, Insteon, UWB, ZigBee and other short and medium range standards. These technologies allow you to quickly organize data transmission between the sensor and the receiving module, especially in cases where the monitored object has a complex geometry or is located in a hard-to-reach place.

The Star Network topology is one of the basic structures for organizing modern wireless and wired networks, providing high flexibility, scalability and reliability. In this configuration, all peripheral nodes (sensors, measurement modules, actuators) are connected to one central node – a controller, gateway or base station, which performs the functions of managing and routing data flows.

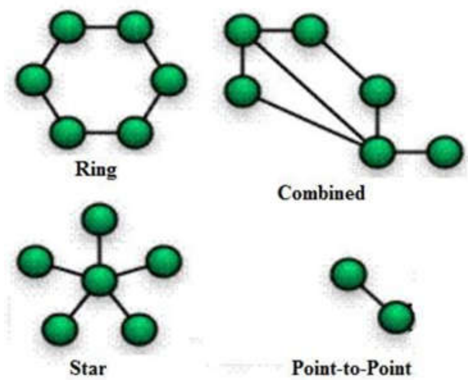

Figure 2 – Types of wireless sensor network topologies

The star topology is the basis for many modern wireless standards that are widely used in industrial diagnostic systems. Such technologies include Wi-Fi, Insteon, ZigBee, UWB, iDEN, CDMAOne, WiMAX, GSM,

GPRS, UMTS, and others. The use of these protocols provides different levels of range, bandwidth, and power consumption, which allows you to adapt the network to specific control tasks: local measurements, monitoring large areas, transmitting high-resolution signals, or organizing communication with remote objects

Combined topology (multicell network). Combined or multicell topology (multicell / mesh network) is one of the most stable and flexible structures for organizing modern wireless networks. It originates from the fully connected topology, in which each node can have several paths to connect to other nodes. Unlike the classic fully connected structure, in multicell networks not all possible connections are necessarily present, but multiple route exchange remains available, which ensures high reliability.

When organizing multi-cell networks, it is necessary to take into account the increased load on routing nodes, more complex configuration schemes and higher energy requirements, especially in the case of network-centric NK systems with a large number of autonomous sensors. Combined or multi-cell topology is characteristic of many modern wireless technologies, such as UWB, Wi-Fi, Insteon, ZigBee, iDEN, CDMAOne, Wi-MAX, GSM, GPRS, UMTS. Some of them (for example, ZigBee or UWB) directly support mesh functionality at the protocol level, ensuring efficient data exchange between a large number of nodes.

Ring Network topology involves organizing the network in the form of a closed loop, in which each node is connected to two neighboring ones, forming a continuous path for transmitting information "in a circle". In such a structure, each device acts as a receiver and transmitter at the same time, relaying signals further along the ring to the next node. Although the classical ring topology is most typical for wired networks, in wireless systems it can be used in some cases, in particular for organizing data transmission between a number of stationary or stationary sensors arranged in a structural ring configuration. This is possible when each node is able to stably transmit the received data further, ensuring a closed circulation of information.

Some modern wireless technologies can support ring transmission schemes, although they do not use them as the underlying topology. These include: UWB, Wi-Fi in relay modes, ZigBee (with specific routing settings), Insteon, and other protocols that support serial relay.

Thus, the "ring" topology, although rarely used as the main one in wireless networks, still finds its application in specialized automated non-destructive testing systems. It is useful where the structure of the object or the features of the technological process require the organization of information transmission "in a circle", and each sensor can act as a receiving and transmitting node.

A comparative analysis of the application of technologies and topologies is presented in Table 2.

Table 2 – Comparative analysis of the application of technologies in wireless network topologies

Techno logy	Point– point	Star	Ring	Mesh / multi-cell
Bluetoo th	✓	Partiall y (via central device)	×	×
ANT	✓	×	×	×
RFID	✓ (reader –tag)	×	×	×
RuBee	✓	×	×	×
PDC	✓	×	×	×
Wi-Fi	✓ (in P2P modes)	✓	Limited	Partially (due to Wi-Fi 6/6E mesh modes)
Insteon	✓	✓	Limited	✓
UWB	✓	✓	Can be used	✓
ZigBee	✓	✓ (ZigBe e star)	Maybe in some scenari os	✓ (ZigBee mesh)
iDEN	×	✓	×	Limited
CDMA One	×	✓	×	×
WiMA X	×	✓	×	×
GSM	×	✓	×	×
GPRS	×	✓	×	×
UMTS	×	✓	×	×

Conclusions

The paper considered modern wireless information transmission technologies and their application in automated NDT systems, as well as the main topologies of wireless networks used to organize monitoring of the technical condition of equipment.

The analysis showed that wireless systems are becoming an integral part of industrial processes, providing mobility, speed of data collection and the ability to remotely control complex objects. The most common technologies at the industrial level are Bluetooth, Wi-Fi, WiMAX, GPRS, which are used in local production areas to solve specialized tasks. Their characteristics - data transfer speed, range and resistance to interference - make them effective for working with sensors and NDT devices. The use of these technologies allows you to increase the efficiency of automated NDT systems, reduce the risk of accidents and improve product quality management at all stages of production.

As for the organization of networks, the main wireless network topologies used in NK systems were considered: point-to-point, star, multi-cell (mesh), cluster tree and ring. Each of them has its own advantages and limitations: the point-to-point topology is simple and reliable for two nodes, the star provides centralized management and scalability, the multi-cell network allows for the implementation of self-healing systems with high fault tolerance, the cluster tree optimizes data transmission in large distributed networks, and the ring topology can be used for specialized systems with sequential data transmission, where each node acts as a transceiver.

Thus, the combination of modern wireless technologies and a properly selected network topology allows you to create effective, reliable and scalable non-destructive testing systems capable of ensuring the safe operation of complex industrial facilities, operational monitoring of the condition of materials and structures, as well as data integration into forecasting and analytics systems.

Acknowledgements
None.

Conflict of interest
None.

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БЕЗДРОТОВІ ТЕХНОЛОГІЇ ПЕРЕДАЧІ ІНФОРМАЦІЇ В АВТОМАТИЗОВАНИХ СИСТЕМАХ НЕРУЙНІВНОГО КОНТРОЛЮ

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Анотація. У статті представлено аналіз сучасних технологій бездротової передачі інформації та їх застосування в автоматизованих системах неруйнівного контролю (НДК). Розглянуто основні бездротові протоколи, що використовуються в промисловості, зокрема Bluetooth, Wi-Fi, UWB, GPRS, а також новітні рішення для розподілених сенсорних мереж нового покоління. Кожна технологія оцінюється за критеріями дальності, швидкості передачі даних, енергоспоживання та стійкості до перешкод, що дозволяє визначити їх доцільність для різних видів неруйнівного контролю, включаючи моніторинг стану металевих конструкцій, трубопроводів, резервуарів, елементів авіації та суднобудування, а також обладнання атомних та хімічних підприємств. Значна увага приділяється топологіям бездротових мереж, серед яких розглянуто точка-точка, зірка, багатостільникова (mesh) та кільцева. Представлено порівняння їх характеристик з точки зору надійності, масштабованості, складності конфігурації та ефективності інтеграції в промислові об'єкти. У контексті неруйнівного контролю (НК) топології визначають не лише ефективність передачі даних, але й здатність мережі забезпечувати відмовостійкість та безперервний моніторинг критичних об'єктів, де втрата зв'язку навіть на короткий час може призвести до ненадійної оцінки технічного стану. У статті показано, що правильне поєднання сучасних технологій та відповідної топології дозволяє створювати масштабовані, надійні та енергоефективні системи НК, які можуть забезпечити своєчасне виявлення дефектів, прогнозувати стан матеріалів та конструкцій, а також підвищити безпеку виробничих процесів. Крім того, використання бездротових мереж спрощує організацію дистанційного моніторингу, зменшує потребу у фізичному доступі до об'єктів та дозволяє інтегрувати дані з різних джерел у діагностичні системи.

Ключові слова: неруйнівний контроль, зіркоподібна топологія, бездротова передача даних, вимірювання параметрів, система збору даних.