RESEARCH OF DATA TRANSMISSION NETWORKS IN MANUFACTURING SYSTEMS

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Annotatsiya: Ushbu maqolada avtomatlashtirilgan ishlab chiqarish muhitlarida qo‘llaniladigan sanoat ma’lumot uzatish tizimlari tahlil qilinadi. Aloqa arxitekturalari, ishlash prinsiplari hamda real vaqt rejimi, ishonchlilik, xavfsizlik, masshtablanuvchanlik va shovqinga chidamlilik kabi texnik talablariga nisbatan o‘rganilgan. Industrial Ethernet, Modbus, PROFIBUS, CAN/CANopen, OPC UA, EtherCAT, MQTT, 5G va Time-Sensitive Networking (TSN) kabi zamonaviy simli va simsiz sanoat aloqa texnologiyalari tahlil qilingan. Ishlab chiqarish jarayonlari uchun xos bo‘lgan besh pog‘onali avtomatlashtirish piramidasi asosidagi ko‘p darajali sanoat tarmoq arxitekturasi qaralgan. Shuningdek, sanoat tarmoqlarida uchraydigan texnik, tashkiliy va kiberxavfsizlik muammolari aniqlanib, ularni bartaraf etishning samarali usullari ko‘rib chiqilgan. Tadqiqot ishida sanoat tizimlarida barqaror, xavfsiz va deterministik ma’lumot almashinuvini ta’minlashda protokollarni to‘g‘ri tanlash muhimligini asoslab berilgan.

Kalit so‘zlar: Sanoat aloqa tizimlari, ma’lumot uzatish, Industrial Ethernet, real vaqt tarmoqlari, avtomatlashtirish piramidasi, SCADA, PLC, OPC UA, EtherCAT, Internet buyumlari, Industry 4.0, kiberxavfsizlik.

Аннотация: В данной статье анализируются системы передачи промышленных данных, применяемые в автоматизированных производственных средах. Рассматриваются архитектуры связи, принципы функционирования, а также технические требования, включая работу в реальном времени, надёжность, безопасность, масштабируемость и помехоустойчивость. Проанализированы современные проводные и беспроводные промышленные технологии связи, такие как Industrial Ethernet, Modbus, PROFIBUS, CAN/CANopen, OPC UA, EtherCAT, MQTT, 5G и Time-Sensitive Networking (TSN). Рассмотрена многоуровневая архитектура промышленной сети, основанная на пятиуровневой пирамиде автоматизации, характерной для производственных процессов. Кроме того, выявлены технические, организационные и кибербезопасностные проблемы, возникающие в промышленных сетях, и рассмотрены эффективные методы

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их устранения. В работе обоснована важность правильного выбора протоколов для обеспечения стабильного, безопасного и детерминированного обмена данными в промышленных системах.

Ключевые слова: Промышленные системы связи, передача данных, Industrial Ethernet, сети реального времени, пирамида автоматизации, SCADA, PLC, OPC UA, EtherCAT, Интернет вещей, Индустрия 4.0, кибербезопасность.

Abstract: This article analyzes industrial data transmission systems used in automated manufacturing environments. Communication architectures, operating principles, and technical requirements such as real-time operation, reliability, security, scalability, and noise immunity are examined. Modern wired and wireless industrial communication technologies, including Industrial Ethernet, Modbus, PROFIBUS, CAN/CANopen, OPC UA, EtherCAT, MQTT, 5G, and Time-Sensitive Networking (TSN), are analyzed. A multi-level industrial network architecture based on the five-level automation pyramid typical of production processes is considered. In addition, technical, organizational, and cybersecurity challenges encountered in industrial networks are identified, and effective methods for their mitigation are discussed. The study substantiates the importance of selecting appropriate communication protocols to ensure stable, secure, and deterministic data exchange in industrial systems.

Keywords: Industrial communication systems, data transmission, Industrial Ethernet, real-time networks, automation pyramid, SCADA, PLC, OPC UA, EtherCAT, Internet of Things, Industry 4.0, cybersecurity.

Introduction.

The present study is aimed at analyzing the types, operating principles, and requirements imposed on industrial data transmission systems, as well as the advantages and limitations of modern technologies.

Today, automated control systems, robotic production lines, intelligent sensors, and digital monitoring tools have become integral components of manufacturing, thereby defining the quality of the data transmission infrastructure that supports them.

Review of Literature. In industrial processes, data transmission systems represent a combination of hardware and software components that enable information exchange among various devices, sensors, control units, and central servers. These systems provide the information flow required for real-time monitoring, control, and optimization of production processes [1,5].

From this perspective, an in-depth study of the distinctive features of data transmission systems is a relevant task in the context of ongoing digital transformation. Reliability, speed, security, flexibility, and scalability of these

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systems are key factors determining the level of technological development of industrial enterprises.

Sensors and measuring instruments continuously monitor technological parameters—such as pressure, temperature, speed, vibration, and flow rate—and transmit them to control systems.

These data are subsequently processed by control systems such as PLC, DCS, or SCADA [2].

In addition, data transmission systems are not limited to communication among field-level devices but are also integrated with higher-level servers, data storage systems, and cloud platforms. Large-scale digitalization of production processes based on Industry 4.0 and IoT (Internet of Things) technologies further increases the importance of these systems [4].

Problem statement. Various communication technologies and protocols are used for data transmission in industrial processes. Their selection depends on the production environment, transmission distance, security requirements, latency constraints, and network load. In general, these technologies are classified into wired and wireless communication systems.

Table 1.

Data Transmission Network Protocols in Industrial Systems.

Wired technologies		
1.	Ethernet and Industrial Ethernet	− **Standard Ethernet Protocol (Conventional Ethernet)** is widely used; however, in industrial environments, its enhanced version - **Industrial Ethernet -** is employed. − It provides high data transmission speed, real-time operation (determinism), and additional protection mechanisms. − It operates based on protocols such as **PROFINET**, **EtherCAT**, and **EtherNet/IP**.
2.	Modbus (Modbus RTU, Modbus TCP)	− One of the simplest and most reliable industrial protocols. − Widely used in IoT and SCADA systems. − It provides the ability to easily integrate devices from different manufacturers.
3.	PROFIBUS	− A highly robust protocol widely used in automated systems. − It simplifies integration between sensors, actuators, and controllers.
4.	CAN / CANopen	− Widely used in the transportation and automotive industries. − Suitable for systems requiring high reliability and low latency.
Wireless technologies		

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1.	Wi-Fi (WLAN)	– Easy to install, cost-effective, and provides high data transmission speed. – However, in industrial environments, susceptibility to interference can be high.
2.	Bluetooth Low Energy (BLE)	– Suitable for sensors requiring low power consumption. – Designed for use over short distances.
3.	ZigBee	– Used in large-scale sensor networks (mesh-type networks). – Requires low power consumption and ensures reliable data transmission.
4.	LoRaWan	– Designed for long-distance data transmission. – Ideally suited for low-power IoT devices.
5.	5G technologies	– Provides ultra-low latency (up to 1 ms), very high speed, and stable connectivity. – Considered a key industrial technology of the future. – Suitable for robotics, autonomous vehicles, and real-time monitoring.
Real-Time technologies		
1.	EtherCAT	– **Industrial Ethernet with Low-Latency operation**
2.	Profinet IRT	– **Capability for synchronous Real-Time operation**
3.	Time-Sensitive Networking (TSN)	– **Time-Sensitive Networking (TSN) technology**, which is expected to become the future standard for Industrial Ethernet.

Most industrial processes require real-time operation, meaning that data must be transmitted with minimal delay. The types of such transmission are discussed in t**able 1** below.

The correct selection of data transmission technology is crucial for the reliability, security, and speed of an industrial system. Each technology has its advantages and limitations, which are applied depending on the type of production process [6].

Since the industrial environment is more complex compared to other information systems, the data transmission infrastructure must meet a number of specific requirements. Such systems should possess special characteristics, including real-time operation, high reliability, security, scalability, and compatibility with various devices.

1. **Reliability.** Any failure or error in data transmission in industrial processes can lead to process stoppage, equipment malfunction, or safety hazards.

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2. **Security.** Industrial systems must be highly secure from a cybersecurity perspective, as any cyberattack can result in a complete production halt.

Security is a key criterion for industrial networks, ensuring confidentiality and integrity of transmitted data.

3. **Responsiveness and latency.** Many industrial processes require real-time control.

4. **Scalability.** Modern industrial enterprises have a large number of sensors, robots, controllers, and monitoring devices.

5. **Adaptability and integration.** In industrial systems, devices from different manufacturers need to work together. Therefore, it is important for systems to have adaptive and open architecture.

6. **Noise immunity.** Industrial environments contain high levels of electrical noise, electromagnetic waves, and mechanical vibrations.

7. **Energy efficiency.** Energy efficiency is especially important for IoT devices, wireless sensors, and remote stations.

All these measures ensure uninterrupted system operation.

Distinctive features of industrial data transmission systems include reliability, speed, security, scalability, and adaptability. These requirements ensure continuous and stable operation of industrial processes and facilitate the implementation of Industry 4.0 technologies.

Protocols used in industrial manufacturing and their differences. In industrial processes, specialized industrial protocols are used for data transmission. They provide reliability, speed, noise immunity, and compatibility between different devices in the network. Each protocol has its specific purpose, advantages, and application areas. These are summarized in **Table 2.**

Table 2:

Protocols and Technologies for Industrial Networks

№	Protocol type	Purpose	Advantages	Disadvantages
1.	Modbus	One of the most common and simple protocols in the industrial sector.	− Extremely simple structure. − Wide compatibility between different devices. − Low cost and easy to integrate.	− Not suitable for complex topologies. − Low level of security.
2.	Modbus RTU (based on RS-485)	Wired, slow, but stable.		

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3.	Modbus TCP (based on Ethernet)	Operates at high speed.		
4.	Profibus	A highly reliable industrial protocol developed by Siemens.	– Stable real-time operation. – Long-distance data transmission. – Suitable for multi-device networks.	– Installation and configuration are complex. – Speed is lower compared to modern Industrial Ethernet protocols.
5.	Profibus-DP	For sensors and actuators.		
6.	Profibus-PA	For hazardous areas with explosion risk (intrinsically safe).		
7.	Profinet	A modern high-speed protocol based on Industrial Ethernet.	– Ultra-low latency. – Suitable for robotics and real-time systems. – High scalability. – Enhanced security mechanisms.	– Equipment cost is higher compared to other protocols. – Proper system configuration requires technical expertise.
8.	CAN (Controller Area Network)	Widely used in automotive and transportation systems, but also applied in industrial sectors.	– High noise immunity. – Low latency. – High reliability.	– Limited long-distance transmission capabilities. – Does not reach the performance level of Ethernet-based protocols.
9.	CANopen	A highly adaptive protocol based on CAN.		
10.	OPC UA	One of the most modern and secure protocols, enabling data exchange between industrial information systems.	– Platform-independent. – Strong security and encryption. – Integration with cloud systems. – Suitable for IoT and Industry 4.0.	– Complex architecture. – Requires significant resources.

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11.	EtherCAT	**Industrial Ethernet protocol optimized for real-time operation.**	– Latency below one millisecond. – High synchronization accuracy. – Suitable for real-time servo systems.	– Initial configuration is complex. – Requires specialized equipment.
12.	MQTT	A lightweight protocol used for IoT sensors, remote monitoring, and low-power networks.	– Requires low traffic. – Operates reliably over long distances. – Compatible with cloud systems.	– Not suitable for hard real-time systems. – Security depends on the broker.

The advantages and limitations of each protocol are determined by the requirements of the production process.

In industrial enterprises, data transmission is organized based on a strictly structured multi-level architecture [7].

Table 3.

Comparative Analysis of Protocols

Protocol	Responsiveness (Speed / Latency)	Security	Distance	Compatibility (Flexibility)	Application Area
Modbus RTU/TCP	Medium	Low	Medium	High	SCADA, sensors
Profibus	Medium	Medium	High	Medium	Heavy industry
Profinet	Very high	High	Medium	High	Robotics, automation
CAN/CANopen	High	Medium	Low	Medium	Transportation, industrial processes
OPC UA	Medium	Very high	High	Very high	Industry 4.0, IoT
EtherCAT	Very high	Medium	Low	Medium	Servo systems, real-time applications
MQTT	Low	Medium	Very high	High	IoT, remote sensors

Solution approach. This architecture ensures continuous, secure, and stable information exchange between devices at different levels. Typically, this structure

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is built along the following chain: **Sensor Level → Control Level → Server/Data Center → Cloud.**

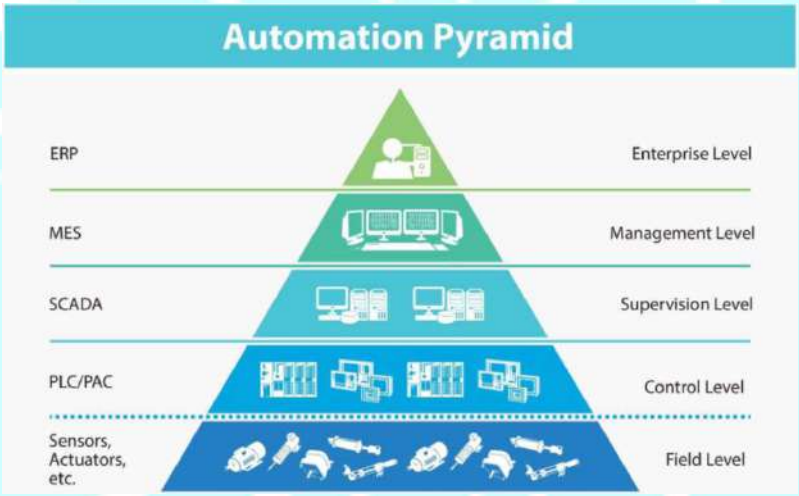


Fig. 1: Five-Level Automation Pyramid

1. **Sensor and field level.** This level consists of devices that directly measure and control the production process: sensors (temperature, pressure, vibration, speed, flow, humidity, etc.), actuators (valves, motors, relays), and embedded sensor systems. Data transmission at this level is carried out using protocols such as **Modbus RTU**, **Profibus**, and **CANopen**. The main requirements at this stage are noise immunity, stability, and accuracy.

2. **Control level.** This level manages production processes in real time. Responsiveness is critical at this level, so protocols suitable for real-time operation are widely used, including **Profinet**, **EtherCAT**, and **Modbus TCP**.

3. **Supervisory and monitoring level.** The **SCADA system** collects all data, visualizes it, archives it, and allows process control. Communication at this level typically uses protocols such as **OPC UA**, **MQTT**, and **Modbus TCP**.

4. **Data center and enterprise level.** At this level, overall enterprise management is performed.

It processes and analyzes production data and serves as the basis for strategic decision-making. Communication is usually conducted via highly secure protocols such as **OPC UA**, **HTTPS**, and corporate **VPNs**.

5. **Cloud technologies and Edge Computing.** In modern industry, cloud technologies and **Edge Computing** play a significant role. Edge Computing is particularly important for processes sensitive to real-time operation.

6. **Network topologies.** Industrial networks are built using various topologies. The choice of topology depends on the complexity of the production process.

7. **General principles of architecture.** Industrial network architecture spans all levels, from sensors to enterprise management systems. The development

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of **Industry 4.0**, **IoT**, and cloud technologies continues to enhance this architecture.

Table 4.

Issues in Industrial Data Transmission Systems and approaches to their solutions

№	Issues	Description	Solutions
1.	**Signal Interference and Noise**	Electrical noise, electromagnetic interference, and mechanical vibrations can distort transmitted data.	− Use of shielded cable types. − Implementation of fiber-optic communication links. − Application of signal filtering and amplification devices. − Use of error correction algorithms in transmission protocols (CRC, checksum).
2.	**Data Loss and Packet Drops**	Communication errors, faulty sensors, or network congestion may cause missing data.	− Network optimization through segmentation in Industrial Ethernet. − Implementation of QoS mechanisms. − Use of low-latency protocols. − Deployment of filters and switch configurations to limit unnecessary traffic.
3.	**Latency and Delays**	Real-time control requires minimal delay, which can be affected by network congestion or long transmission distances.	− Use of universal communication standards. − Deployment of protocol converters (gateways). − Implementation of a technical policy based on unified standards when selecting equipment. − Configuration of the SCADA system to operate with multiple protocols.
4.	**Scalability Challenges**	Adding new devices or sensors may degrade network performance.	− Network segmentation. − Strong authentication and encryption (VPN, TLS). − Regular security updates and audits. − Cybersecurity training for personnel. − Deployment of IDS/IPS monitoring systems.
5.	**Cybersecurity Threats**	Vulnerabilities can lead to unauthorized	− Phased modernization of the existing system. − Replacement of obsolete PLCs with new models.

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		access, data breaches, or operational disruptions.	− Implementation of a scheduled maintenance system. − Keeping backup equipment in a ready-to-use state.
6.	**Compatibility Issues**	Devices from different manufacturers may not communicate effectively.	− Ensuring an uninterrupted power supply using UPS systems and generators. − Using redundant (dual-channel) power supplies for PLCs and servers. − Software development of emergency shutdown scenarios. − Application of automatic restart protocols.
7.	**Power and Energy Constraints**	Wireless sensors or remote stations may have limited energy supply.	− Continuous training of operators and engineers. − Simplification of HMI interfaces. − Automatic logging of configuration changes. − Implementation of clear procedures and rules for operational workflows.

Discussion. The reliability of data transmission systems is crucial for the automation of production processes. However, in real industrial environments, various technical, organizational, and cybersecurity issues arise. Below are the most common issues and strategies for their effective resolution.

Conclusion. Industrial data transmission systems are an integral part of modern industry, ensuring efficiency, continuity, and safety of technological processes. This study analyzed the composition, operating principles, protocols, and practical applications of these systems. In addition, the main challenges encountered in industrial environments and strategies for their resolution were examined.

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