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Application and Development Prospects of Wireless Monitoring Systems in Industrial Enterprises (Uzbekistan as an Example)

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***Abstract*: This article analyzes the importance of wireless monitoring systems in industrial enterprises, their areas of application and their development prospects in the conditions of Uzbekistan. In particular, the advantages of monitoring systems developed based on technologies such as NB-IoT, LoRa, ZigBee, Wi-Fi, ways of their implementation in practice and existing problems are considered. The article analyzes the possibilities of real-time data collection and transmission in the industrial zones of Uzbekistan using the example of an environmental monitoring system developed by the author. Future directions based on artificial intelligence, energy-saving algorithms and digital transformation trends are cited as development prospects.**

***Keywords*: wireless technologies, industry, energy, monitoring, microcontroller, model, NB-IoT, topology.**

1. Introduction

Today, environmental safety, energy efficiency and automation of production processes are among the most important issues in industrial enterprises. In particular, the need to control harmful gases, heat emissions, dust particles and other polluting factors emitted into the environment is growing. Wireless monitoring systems are of great importance for the effective implementation of these tasks. Monitoring systems based on wireless technologies allow ensuring the stability of production processes, collecting and analyzing data in real time, and sending prompt warnings in emergency situations. In the conditions of Uzbekistan, the introduction of such systems at industrial enterprises can increase environmental and economic efficiency. The article analyzes in depth the application of wireless monitoring systems at industrial enterprises, existing capabilities, technologies used and their scientific and technical aspects, using the example of Uzbekistan. It also highlights technological solutions implemented in real practice based on the developed monitoring system and considers their development prospects [1]-[3].

In recent years, wireless monitoring systems have been widely used in various fields around the world: ecology, healthcare, agriculture, industry and transport are examples of this. For example, in the European Union, wireless sensor networks (WSN) are used to continuously monitor NO_2, SO_2, CO_2 and dust particles in the air. In the USA, emission control systems based on NB-IoT technology have been introduced. LoRaWAN technology allows data transmission over long distances (10–15 km), which is very convenient for monitoring systems in rural areas. ZigBee is used as a low-power and reliable communication medium for monitoring temperature, pressure and humidity in industrial buildings [2]-[6].

In Uzbekistan, automated systems have been introduced in industrial enterprises in recent years as part of the digital transformation strategy. However, the widespread implementation of wireless monitoring systems is still at an early stage. In most cases, monitoring systems are organized on the basis of wired communication, which creates difficulties in technical maintenance.

2. Analysis of Wireless Technologies

For example, in environmental monitoring, Uzbekistan relies mainly on laboratory analysis and stationary equipment, compared to the experience of the United States or Europe. This limits the possibilities of real-time monitoring. Therefore, the development of monitoring systems based on wireless technologies is relevant [7]-[10].

NB-IoT (Narrowband Internet of Things) NB-IoT is a narrowband, low-power, wide-area wireless communication technology that is ideal for industrial monitoring.

Its main advantages:

- low energy consumption (10-year battery life),
- high coverage (up to the interior of buildings),
- low-cost modules (SIM7020E, BC95, etc.).

LoRaWAN is used to transmit data over long distances. It operates at low speed but with high reliability. In industrial areas, each LoRa Gateway can work with thousands of sensors.

While Wi-Fi is more suitable for high-speed data transmission, ZigBee is suitable for small networks and short-range monitoring. ZigBee's energy-saving mode makes it suitable for environmental monitoring devices.

The ESP32 microcontroller integrates Wi-Fi and Bluetooth, is inexpensive, has a powerful processor, and can control many sensors. This device is widely used as the “core” of wireless

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Table 1
Analysis of wireless technologies

Feature	LoRa	Zig Bee	Wi-Fi	NB-IoT	Blue tooth
Operating frequency	433/868/915MHz	2.4 GHz	2.4/5GHz	800-2100MHz	2.4 GHz
Transmission distance	2-15 km	10-100 m	50-200 m	1-10 km	10-100 m
Data transfer rate	0.3-50 kbps	20-250 kbps	11-600 Mbps	20-250 kbps	1-3 Mbps (Classic), 1 Mbps (BLE)
Energy consumption	Very low	Low	High	Very low	Average
Networking opportunity	1-10 thousand	65 thousand	32 devices	Million	7 devices
Night-time transmission (latency)	High (seconds)	Average (10-100 ms)	Very low (1-10 ms)	High (1-10 s)	Low (10-100 ms)
Areas of application	IoT, environmental monitoring	Home automation , industry	Video, high speed	Smart city, industry	Short-range communication
Security	AES-128	AES-128	WPA2/WPA3, AES-256	SIM authentication, AES-128	AES-128 (BLE)
Advantages	Large radius, low power	Flexible, wide-ranging	High speed	Long range, ideal for IoT	Low energy, widely used
Limitations	Low speed, delay	Low speed, short distance	High power consumption	Delayoperator dependency	Short distance, limited connectivity

monitoring systems [11]-[15].

The table 1 lists the most commonly used wireless technologies—LoRa, ZigBee, Wi-Fi, NB-IoT, and Bluetooth—and their level of adaptability for industrial monitoring: Table 1.

Based on this analysis, it appears that LoRa and NB-IoT technologies are the most suitable for industrial monitoring. Because they:

- works over a long distance (1–15 km);
- requires little energy (can work up to 10 years);
- has the ability to expand the sensor network.

ZigBee is suitable for small areas and inside industrial buildings. Although Wi-Fi and Bluetooth technologies transmit data at high speeds, they have limited capabilities for long-term monitoring devices due to their high power consumption [16]-[19].

Network topology is the logical structure of how devices in a wireless monitoring system are arranged and connected to each other. By choosing the right topology, you can:

- system efficiency increases,
- energy is saved,
- faults are easily detected,
- The coverage area will be expanded.

The following basic topologies are widely used in wireless sensor networks:

Star topology - all sensors communicate with one central node (gateway or microcontroller). Each sensor communicates directly with the hub only Figure 1.

Advantages:

- The t -interruption is simple.
- easy to maintain
- low latency, easy central management

Disadvantages:

- If the center fails, the entire system fails.
- limited coverage

Application:

- indoor industrial monitoring (inside the building)
- in energy-limited areas.

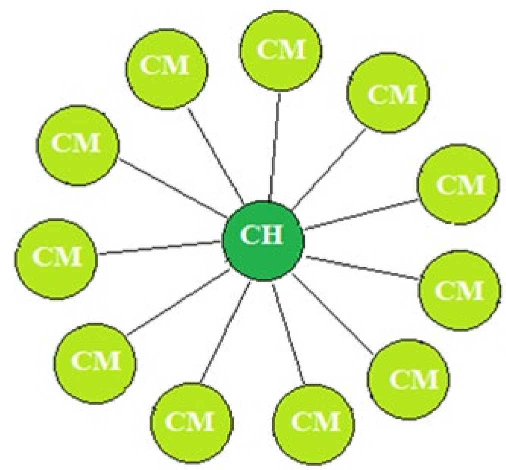

Fig. 1. Star topology

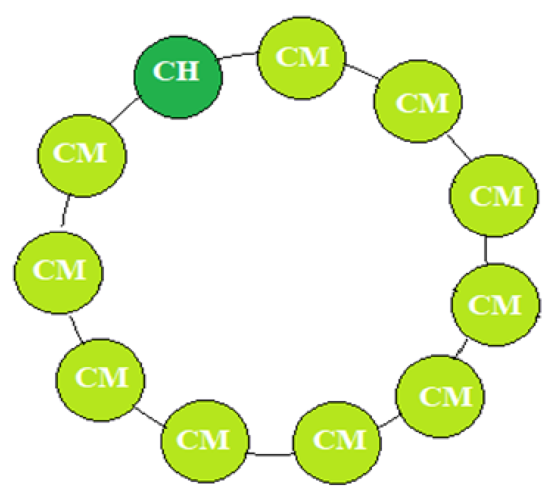

Fig. 2. Ring topology

Ring topology - each node is connected to only two neighboring nodes and data is transmitted along the ring. Figure 2.

Advantages:

- wires or communication resources are rarely used
- easier to manage

Disadvantages:

- If one node fails, the entire loop can fail.
- no redundancy

Application:

- at industrial facilities with nearby equipment.

Mesh topology - each node is connected to several other nodes. Data travels through different paths to find its way to the desired destination Figure 3.

Advantages:

- high reliability (if one node fails, there is an alternative path)
- easy to expand coverage
- distributed management

Disadvantages:

- programming and configuration are complicated
- higher power consumption

Application:

- wide-area ecological monitoring (riverbank, mountain area)
- large industrial zones

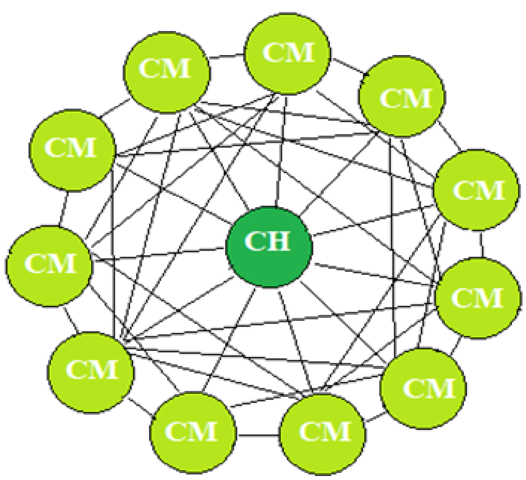

Fig. 3. Mesh topology

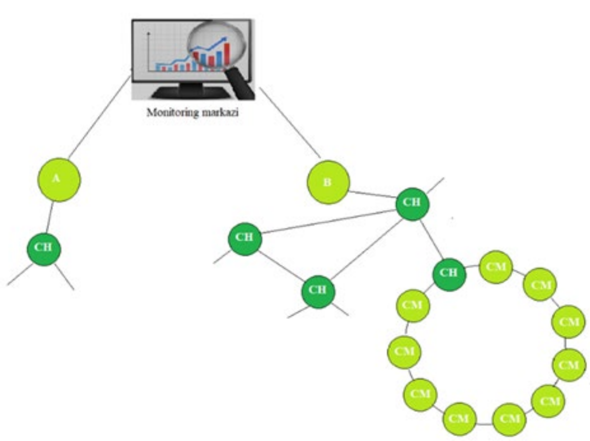

Fig. 4. Hybrid topology

Hybrid topology - This is a combination of different topologies (e.g. Star + Mesh). Typically, a star or mesh is used in the core, while the edge nodes are connected in a simplified way Figure 4.

Advantages:

- flexible
- the optimal solution is applied to each zone
- wide coverage + reliability

Disadvantages:

- project and setup is complicated.
- It is necessary to manage resources carefully.

Let's consider a mathematical model of wireless monitoring systems.

To evaluate and optimize the effectiveness of wireless monitoring systems, it is important to develop mathematical models of them. Through these models:

- communication reliability,
- signal loss,
- energy consumption,
- data transfer speed,
- system efficiency is determined and optimized.

Path Loss Model - In wireless communication systems, signal strength decreases with distance. This loss is expressed by the following formula:

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X\sigma \qquad (1)$$

- *PL (d)* -d distance loss (dB),
- *PL (d_0)* - signal loss at the initial distance (usually at 1 m),
- *n* - loss coefficient (depends on the environment, usually 2–4),
- X_s is the log-normal random attenuation (dB).

This model is used to estimate signal stability in LoRa, ZigBee, and NB-IoT networks. In industrial areas with lead walls or metal structures, n =3 may be higher [20], [21].

Energy consumption model.

The energy efficiency of the system relies on the following basic formula:

$$E = P \cdot t \qquad (2)$$

Here:

E - total energy consumption (Joules),

P - power consumption (Watt),

t - processing time (seconds).

If the NB-IoT module operates for 30 seconds at 0.2 W of power:

$E=0.2 \cdot 30=6J$

This means that approximately 6 joules of energy are consumed in a single data transfer.

Latency model. Latency in monitoring systems consists of the following components:

$$T_{total} = T_{sense} + T_{process} + T_{transmit} + T_{receive} \qquad (3)$$

Here:

- T_{sense} - sensor data collection time,
- $T_{process}$ - microcontroller processing time,
- $T_{transmit}$ - transmission time (depends on the type of connection),
- $T_{receive}$ - reception time.

In NB-IoT, latency is typically in the range of 1–10 seconds, while in Wi-Fi and ZigBee, it is around 10–100 ms.

Monitoring efficiency model

Monitoring effectiveness is determined by the data transmitted and successfully received in the system:

$$Q = \frac{N_{real}}{N_{total}} * 100 \quad (4)$$

Here:

- N_{real} - the number of successfully transmitted data,
- N_{total} - the total number of packets attempted to be transmitted.

If 930 out of 1000 packets arrive successfully:

$$Q = \frac{930}{1000} * 100\% = 93\%$$

This means that the system reliability is 93%.

The mathematical models above:

- theoretical analysis of the monitoring system,
- assessment of technical capabilities,
- choosing the most appropriate technology,
- necessary to save energy and optimize transmission.

The possibilities for designing, identifying and improving environmental monitoring systems based on these models are expanding at Uzbek industrial enterprises.

3. Conclusion

The implementation of wireless monitoring systems is becoming increasingly important in order to ensure environmental safety and effectively manage production processes at industrial enterprises. This article provides an in-depth analysis of monitoring systems developed in Uzbekistan based on advanced wireless technologies such as NB-IoT, LoRa, ZigBee, and Wi-Fi, and compares each of them with their technical capabilities, advantages, and limitations. According to the results of the analysis, it was determined that NB-IoT and LoRa technologies with long range, low energy consumption, and high reliability are the most optimal solutions for industrial areas of Uzbekistan. ZigBee and Wi-Fi are effective in short-range, high-speed monitoring. The article also analyzes various topologies of wireless networks (star, ring, mesh, hybrid) and their flexibility, coverage, and reliability. The possibilities of assessing and optimizing the efficiency of systems based on mathematical models of monitoring systems (signal loss, energy consumption, latency, and efficiency) are revealed. In particular, real-time monitoring, energy efficiency, transmission quality and network stability considerations play an important role in further improving the systems. In conclusion, the development of wireless monitoring systems in industrial enterprises of Uzbekistan serves to increase environmental and economic efficiency. In this direction, the creation of new generation monitoring systems based on artificial intelligence, digital transformation and energy-saving algorithms remains one of the main tasks for the future.

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