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APPLICATION OF IOT PROTOCOLS IN SURFACE WATER POLLUTION MONITORING SYSTEMS

Abstract. The rapid pace of industrial growth and the rise in consumerism are increasingly contributing to the deterioration of water quality, posing significant risks to both ecological systems and human health. The urgent need for effective monitoring of water resources to mitigate pollution and ensure the sustainability of these vital ecosystems has never been more apparent. The integration of Internet of Things (IoT) technologies into surface water monitoring presents a transformative approach to addressing these challenges. By automating the collection and transmission of data on water quality, IoT technologies offer a leap forward in our ability to efficiently monitor and manage environmental health. This article explores the application of various data transmission protocols, including Wi-Fi, Zigbee, LoRa, NB-IoT, and BLE, in the context of IoT-enabled water resource monitoring systems. Considerable attention was paid to determining the physical conditions of operation and the limitations they impose on the functioning of water monitoring systems. Each protocol is examined for its potential advantages and limitations in terms of energy efficiency, transmission range, and reliability under the specific conditions encountered in surface water monitoring. Through a comparative analysis, this study not only highlights the distinctive features and suitability of each protocol but also proposes a comprehensive framework for selecting the most appropriate technology based on the specific requirements of water monitoring projects. The findings of this research underscore the critical role of IoT technologies in advancing environmental monitoring and offer valuable insights for the development of more effective and sustainable water quality management strategies.

Keywords: IoT; water monitoring; LoRa; Zigbee; NB-IoT; Wi-Fi; BL; Bluetooth.

INTRODUCTION

One of the core principles envisaged in the Sustainable Development Goals framework, endorsed by the United Nations, for all countries around the world, is to ensure the availability and sustainable management of affordable and safe drinking water and sanitation for all [16]. At the same time, according to the World Health Organization, nearly 30% of the global population (2 billion people) did not have access to a safely managed drinking water service — that is, one located on premises, available when needed, and free from contamination in 2020 [17]. These statistics emphasize the urgent need for advancing water monitoring policies and strengthening control over the quality of groundwater conditions, as well as in rivers, lakes, and oceans.

Apart from the impact on public health, water monitoring is essential for addressing the challenges posed by climate change, providing emergency response and mitigating natural disasters' impact on the community, food safety, and infrastructure maintenance preventing issues in water distribution systems. Also, data collection and management in water monitoring systems, enabled by the use of the IoT concept, may contribute to informed decision-making by governments in terms of preserving a safe environment for both current and future generations.

The Internet of Things (IoT) is a system of interconnected electronic and mechanical devices that have specific identifiers and the capability to automatically exchange necessary data over communication networks [1]. Each IoT device is essentially a computing machine with connected peripherals (sensors, relays, etc.) that invariably has the ability to send or exchange data with a control centre (often a server).

In the last decade, IoT-aided technology has mechanized the maneuvers of several systems, relevant to medical technology, transport, military, smart home appliances, and power grids [26]. Today, IoT technologies can be encountered in virtually any field, from classic "smart" homes and monitoring systems to medical and military devices [9]. Examples include "smart" electricity and water meters, air pollution monitoring systems, wearable blood pressure and pulse trackers, geolocation tracking systems, and more. Such progress in the use of IoT would have been hard to imagine even 5 years ago. With over 7 billion IoT devices connected today, experts anticipate this number to reach 22 billion by 2025 [27].

One of the main factors behind the rapid development of IoT has been the relentless process of increasing the power of microcontrollers, and compact computers, and the advancement of information networks. Continuous improvements in software (frameworks, libraries) paired with an increase in educational materials have considerably eased the creation of technical solutions in the IoT domain. However, the primary factor driving the widespread use of IoT technologies has been the reduction in hardware costs, specifically microcontrollers, sensors, and other equipment.

The usage of IoT technologies in monitoring systems enhances data accuracy, response speed to water pollution, and allows for informed decision-making regarding the preservation of water quality. The IoT ecosystem boasts a diverse array of protocols, each tailored to meet specific requirements in terms of power consumption, data transmission rates, and operational range. The methods of using IoT protocols in the task of water resources monitoring were described in the works [2] – [5]. Analyzing the source data, it's easy to understand that there isn't a standardized approach to choosing the transmission protocol between the monitoring station and the server. However, in the author's opinion, surface water monitoring systems have similar use conditions, which allows for classifying protocols and selecting the best ones.

The surface water monitoring system can operate under varying levels of external conditions complexity, which establishes different requirements for the data transmission protocol. The simplest case involves setting up monitoring stations relatively close to power lines, which allows to neglect requirements for energy efficiency and data transmission range. In this situation, most data transmission protocols will complete their task. More challenging scenarios involve using the monitoring station in remote locations far from any infrastructure, where the device must operate autonomously and transmit data over long distances (often several kilometers). However, even these conditions can be complicated by the inability to easily access the station for maintenance (e.g., battery replacement). Examples of such situations might be stations operating in mountain rivers. Considering the aforementioned conditions, data transmission protocols must meet two primary requirements — energy efficiency and a long data transmission range.

IOT DATA TRANSMISSION PROTOCOLS

In this section, we will examine widely used wireless data transmission protocols — Wi-Fi, LoRa, Zigbee, NB-IoT, and BLE in the context of surface water monitoring systems. It's important to understand that energy efficiency and data transmission range for wireless

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protocols are interdependent. By increasing the transmitter's power to improve transmission distance, the device's energy efficiency decreases. Therefore, it's crucial to adjust the transmitter's power according to the distance to the farthest signal receiver. Another factor affecting the data transmission range is the terrain's topography. If a monitoring station is located in a river that flows between mountains, it will be very challenging to transmit a signal to a receiver located beyond those mountains. Such an issue can be resolved using a signal repeater; however, this device consumes a significant amount of energy, making its use resource-intensive in places without power supply.

Wi-Fi

Wi-Fi is wireless network protocol based on the IEEE 802.11 standard which is usually used for local area networks for internet access. The protocol is designed for general-purpose communication, which often results in higher power consumption compared to specialized low-power IoT protocols. This can be a crucial factor for IoT devices that need to operate on battery power for extended periods. Another significant drawback is the limited range of this protocol [29] — tens, not hundreds of meters, which are often required in monitoring systems where devices are located at considerable distances. There's a problem with network density also; in scenarios where a large number of IoT devices need to be connected closely, Wi-Fi can experience interference and congestion issues that could degrade performance [8]. Another challenge with the Wi-Fi protocol is the relatively high price of transmission modules compared to more energy-efficient protocols. It's important to note that Wi-Fi still has advantages like high data rates, quick setup, and compatibility with existing infrastructure [10]. However, the use of Wi-Fi in IoT networks has been decreasing year by year due to the mentioned problems, and it's unlikely to increase again, as its use was driven by the absence of specialized protocols at a certain point in the development of IoT.

LoRa

LoRa is an open radio protocol operating on unlicensed frequencies, designed as a specialized solution for IoT networks. Its support and development are undertaken by the LoRa Alliance, led by IBM. Approximately 170 million IoT devices in 100 countries are believed to be connected through LoRa. LoRa (short for long range) is a spread spectrum modulation technology derived from Chirp Spread Spectrum (CSS) technology [11]. The technology uses data encoding with wideband pulses at frequencies that gradually increase or decrease over time [23]. Advantages of LoRa include low power consumption (simple devices can operate up to 10 years powered by a 1.5 V battery) and relatively high signal penetration, which is useful in densely built-up cities. However, the primary feature of LoRa is its long data transmission range (over 10 km), allowing an entire town to be covered by a single base station. Experimental systems have managed to cover distances of 700 kilometers and beyond; LoRa also has a very good coping ability for burst random interference; for burst lengths less than 1/2 symbol or interference duty cycles less than 50%, LoRa can still demodulate. Despite a sensitivity deterioration of less than 3 dB, LoRa relies on its unique spread spectrum modulation technology to transmit data in environments below 25 dB of noise [13]. The main drawback of LoRa is its relatively low data transmission speed — ranging from 0.018 to 37.5 kbps [12], which doesn't allow for the transmission of large volumes of data, like audio recordings. Let's consider an example of the network architecture of a surface water monitoring system using the LoRa protocol (Fig. 1). Its main components are:

- Monitoring stations, primarily consisting of a microcontroller and various sensors collecting metrics.

- Gateway, which communicates with monitoring stations via radio link and has internet access. The number of gateways in a network can exceed one due to their bandwidth limitations [19].
- A Network Server is a software, responsible for managing the entire network.
- Application servers — server systems that run the end product's application software.

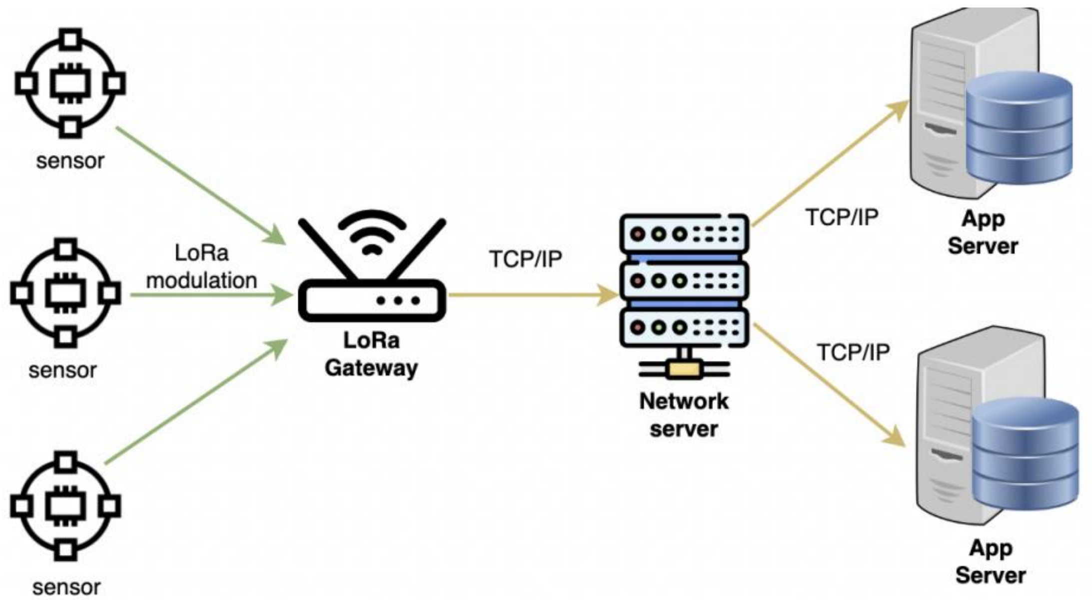

Fig. 1. Architecture of surface water monitoring system network using LoRa protocol

Therefore, we can conclude that LoRa is a suitable protocol for water resource monitoring systems, as they don't transmit large volumes of data and require high energy efficiency and a large operating radius, all of which LoRa fully provides.

Zigbee

Zigbee technology represents a developing wireless network technology characterized by its short-range capability, simplicity, low power consumption, minimal data rates, and cost-effectiveness, implementing the open radio standard IEEE 802.15.4. and is supported by the Connectivity Standard Alliance [20]. It operates in the Industrial, Scientific, and Medical (ISM) radio bands, including 2.4 GHz, 868 MHz in Europe, and 915 MHz in the USA and Australia. Typically, a Zigbee network consists of the following elements Fig. 2):

- Coordinator, which is responsible for initiating and setting up the network, should be the only one in the network. Often, it acts as a bridge or gateway between the Zigbee network and IP-based networks (Internet);
- Router is an optional element that helps expand the network, as it can transmit data between devices;
- End Device, typically these are energy-efficient devices programmed to transmit data for a very short time; they do not participate in routing.

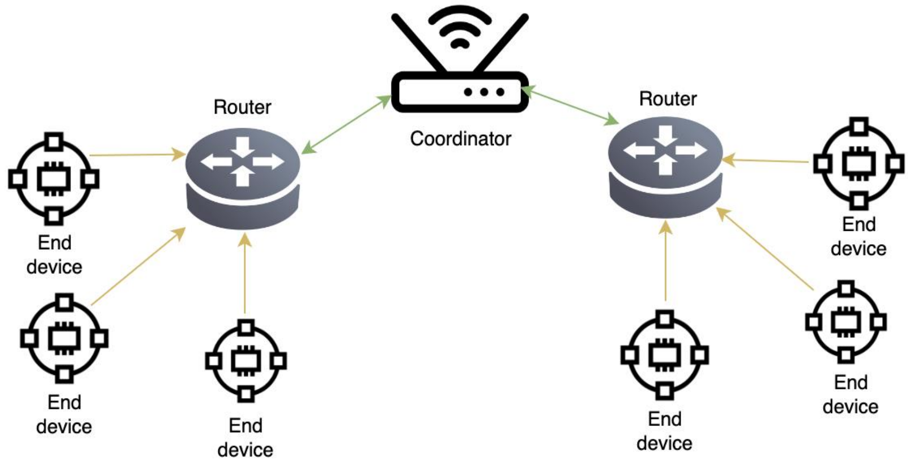

Fig. 2. Architecture of Zigbee IoT network

The main advantages of this technology are efficient energy consumption (though higher than LoRa) and high resilience of the network achieved through distributed topologies — star network, tree network, and mesh network [14]. One of the most significant features of Zigbee is its ability to form mesh networks. In a mesh network, each device (or node) can relay data for other devices, effectively extending the communication range. As a result, in an environment with many Zigbee devices acting as repeaters, the range can be extended over larger areas, potentially spanning several kilometers. The coverage radius of Zigbee can reach hundreds of meters in conditions without obstacles, however, this metric is much lower than that of LoRa, which can transmit data over kilometers. An advantage of the Zigbee protocol is the data transfer speed, which in good conditions reaches 250 kbps, which is much faster than LoRa's speed. Also, Zigbee provides multiple layers of security including AES-128 encryption, link-layer frame protection [6], and support for device authentication [21].

Given the above, one can conclude that the Zigbee protocol is more suitable for a network of devices located in relative proximity (in a building or enterprise) rather than for monitoring a large water area where the data transmission range would not be sufficient.

NB-IoT

Narrowband Internet of Things (NB-IoT) is a Low-Power Wide-Area (LPWA) protocol developed to enable lightweight communication in IoT networks [15]. NB-IoT is a radio technology introduced within the 4G Long Term Evolution (LTE) and 5G mobile networks, specifically designed to allow sensors to transmit data to a server in the cloud over the Internet by relying on the extensive coverage offered by those networks [18]. Mobile network operators worldwide have recently rolled out the NB-IoT technology (commonly referred to as LTE Cat-NB). Its distinct specifications enable it to sustain radio signal connectivity in places where other popular wireless technologies might struggle to establish a data link.

Data transmission is carried out in the cellular network on separate dedicated frequencies and has a speed close to 26 kbs, which is significantly lower than the LTE standard that uses the same network as NB-IoT. The advantages of this protocol include resistance to radio interference and low energy consumption, which, like LoRa and ZigBee devices, allow operation for years from a single power source. NB-IoT also has excellent penetration capabilities. It's capable of connecting devices located deep indoors or in underground environments, which is often challenging for other networks. However, the main advantage of NB-IoT is the ability to work in cellular networks, allowing devices to be installed in field conditions. This advantage is particularly useful for surface water monitoring stations, which are often installed in remote locations without the possibility of deploying the accompanying network infrastructure (gateways, routers, etc.), required by LoRa or Zigbee.

The network structure of the surface water monitoring system using the NB-IoT protocol is depicted in Fig. 3. The primary component of an NB-IoT network is the base station, which is a system of radio equipment for receiving and transmitting radio signals. The main task of the base station is to broadcast the signal to the core network from devices and vice versa. The quality of data transmission over the NB-IoT network directly depends on the location of the nearest base station and its power. The core network (Fig. 3) is the infrastructure mostly located in data-centers responsible for processing and transmitting data to other networks, such as the Internet.

Using a cellular network has its drawbacks, and the main one is the monthly service fee (as of the date of writing the article, servicing one device in Ukraine costs about $5 per year for 60 Mbyte). Another drawback is the inability to control a large portion of the network since it is owned by the operator company, which in certain cases can lead to dependency.

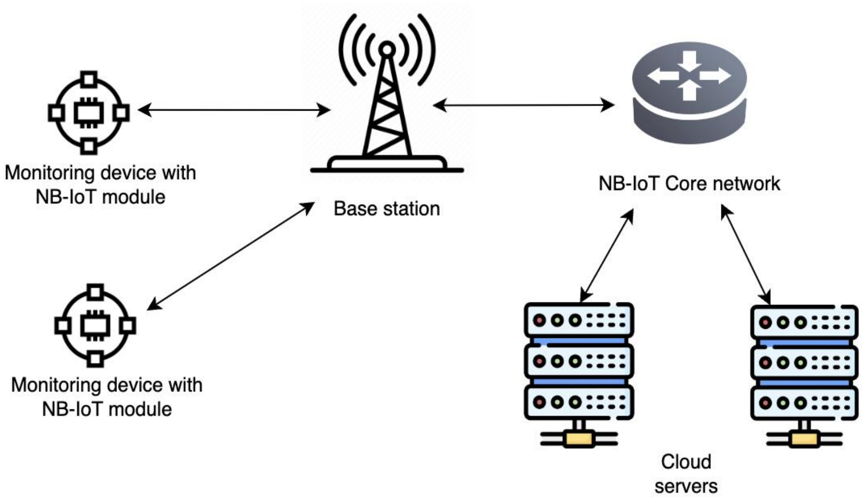

Fig. 3. Architecture of surface water monitoring system network using NB-IoT protocol

Therefore, it can be concluded that NB-IoT is one of the best protocols in the context of water resource monitoring systems, as it addresses the main problem of such systems — physical remoteness from infrastructure. This protocol also fully meets the high energy efficiency requirements of the device, as monitoring stations are often powered by built-in solar panels or batteries.

Bluetooth Low Energy

Bluetooth Low Energy (BLE) was introduced to the world in 2009. It became first available as Bluetooth version 4.0, and since then, it has been the most widely adopted protocol in low-powered devices. BLE is maintained by Bluetooth Special Interest Group and uses Wireless Personal Area Network technology (WPAN) [24]. BLE operates in the ISM frequencies (2.4 GHz), which is a general-use frequency where WiFi and Bluetooth protocols also operate. Radio spectrum of BLE is divided in 40 channels 3 of them are “primary advertizing” channels which are used for establishing a connection and the rest 37 for data transfering. Transmission range of BLE protocol can vary depending on network configuration and transmission conditions and can be in range from 10 meters to 1 kilometer which may be enough for water monitoring systems. Transmission to long distances (over 100 meters) require usage of special data recovery mechanism — Forward Error Correction (FEC) [22]. FEC allows to increase protocol range without increasing transmission power and ensure data packets successful receiving.

One of main advantages of BLE as the name suggests is optimized power usage, allowing devices to run for months or even years on small coin-cell batteries. Power consumptions depends on the chipset being used and the data transfer range. The device's algorithms allow for quick connection and data transmission, followed by extended sleep periods to optimize power consumption and preserve battery life [25]. Data transmission speed of BLE can vary 125–500 kbit/s which is pretty enough for water monitoring systems. One of BLE peculiarirties is Adaptive Frequency Hopping which allows BLE devices to dynamically change transmission frequency to avoid interference with other devices[7] in working spectrum (usually 2.4 GHz) [28].

One of the less obvious advantages of BLE is the ability to use a smartphone as an alternative proxy server for transmitting data to the internet. Theoretically, it's possible to create a mobile application that will utilize the built-in Bluetooth module to read data from devices and subsequently send it to the main servers via the LTE network. Such a data transmission method can be beneficial in cases where wireless networks can't be used due to limited range or in the event of their temporary malfunction. The architecture of such infrastructure is depicted in Fig. 4.

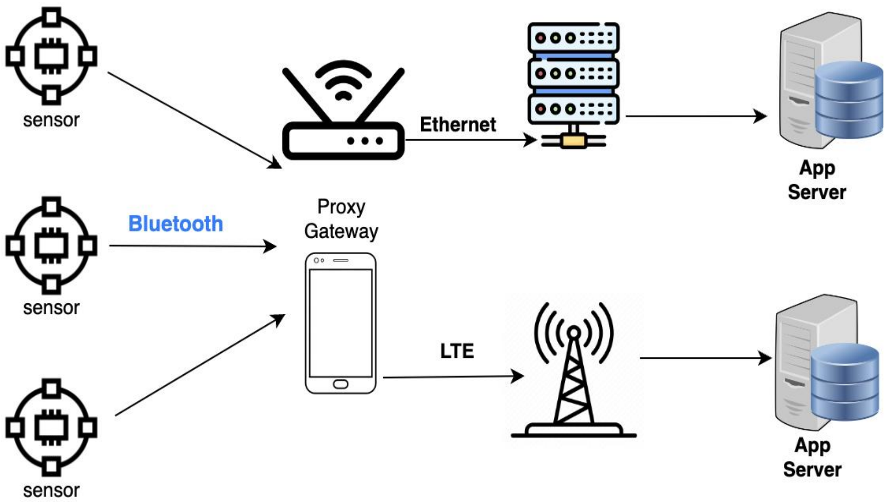

Fig. 4. Architecture of surface water monitoring system network using BLE protocol

Using BLE in surface water monitoring systems is entirely justified, as this protocol meets the main requirements of such systems — a large data transmission range and high energy efficiency. However, BLE is significantly inferior to LORA in transmission range, which under certain conditions can be a critical requirement.

COMPARISON OF DISCUSSED IOT PROTOCOLS AS BEST OPTION FOR WATER MONITORING SYSTEMS

Based on the mentioned information, a comparison table of the main characteristics of IoT protocols was formed into Table 1. It's important to understand that the provided data is approximate and depends on many factors, such as: transmitter power, the presence of radio

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signal obstacles in data transmission locations, and so on. However, the compiled table allows for the comparison of the main characteristics of the protocols under similar data transmission conditions. The column "Energy efficiency" can have values "low" (1–2 months of battery life), "moderate" (several years), and "high" (more than 3 years), which indicates approximately how long a device can operate powered by a relatively small battery. The column "Maximum transmission radius" indicates the maximum data transmission distance in the absence of significant obstacles and with standard transmitter power.

Table 1

Comparison of the main characteristics of IoT protocols

Protocol	Energy efficiency	Maximum transmission radius	Transmission speed
Zigbee	moderate	200m	250 kbit/s
WiFi	low	150m	300 mbit/s
LoRa	high	10 km	35 kbit/s
NB-IoT	moderate	Limited by cellular coverage	60 kbit/s
BLE	moderate	1km	500 kbit/s

Given the abovementioned LoRa may be considered as the best suit protocol for transmitting small volumes of data for long distances, showing the highest energy efficiency among all delineated protocols. In contrast, when applied in relatively short transmission radius (up to 1 kilometer), the performance value of BLE protocols implies the highest productivity with moderate energy consumption over the operation time.

CONCLUSION

Thus, the article examined wireless IoT protocols in the context of their use in surface water pollution monitoring systems. Firstly, a general-purpose local network protocol, Wi-Fi, was discussed. Despite its occasional use in such systems, the author believes such solutions to be mistaken, as this protocol is very energy-intensive and operates within a small radius (Table 1). Wi-Fi can be used in surface water monitoring systems when power supply is available and data transmission radius is small, which significantly narrows the application prospects of such a system. The main advantage of Wi-Fi — data transmission speed, is negated by the absence of the need to transmit large data arrays in such systems.

A more suitable protocol is Zigbee — a solution specifically designed for IoT networks. However, like Wi-Fi, this protocol operates over short distances, making it not the best choice. The problem of a small range can be partially solved by using routers, signal repeaters, and other Zigbee infrastructure, but this complicates the system, introducing other issues. Therefore, Zigbee and Wi-Fi are more suited for local networks (typically up to 100–200 meters), which surface water monitoring systems often aren't.

Close to the established requirements is the IoT protocol BLE, which is quite energy-efficient (comparable to Zigbee) and has a larger operating radius — up to 1 km, which in many cases may be sufficient. Other advantages of BLE include advanced data integrity checking algorithms and interference resistance, making this protocol suitable for mentioned systems within a 1km transmission radius.

The protocol that best meets the requirements is LoRa, as it has the longest data transmission radius and very high energy efficiency (Table 1). However, the protocol offering the most potential is NB-IoT, which uses cellular network infrastructure and has no data transmission distance limits, provided there's connectivity with base stations. This protocol is quite energy-efficient, allowing a device to operate for several years from an autonomous power source (Table 1). It's also necessary to consider the monthly fee for cellular services, making this protocol more expensive than LoRa, especially when many monitoring stations are connected.

In conclusion, in environments where the LoRa protocol can operate, it's better to give preference to it as it can save costs with a significant number of monitoring stations compared to NB-IoT. If there's a need to guarantee data transmission over distances greater than 5 kilometers, the NB-IoT protocol should be used.

The best solution, in the author's opinion, is to combine protocols within one system, namely — equipping monitoring stations close to the receiver with LoRa transmitters, and the most remote ones with NB-IoT.

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ЗАСТОСУВАННЯ ПРОТОКОЛІВ IOT В СИСТЕМАХ МОНІТОРИНГУ ЗАБРУДНЕННЯ ПОВЕРХНЕВИХ ВОД

Анотація. Швидке зростання кількості населення планети, розвиток промисловості та культури споживання все більше сприяють погіршенню якості води, створюючи значні ризики як для екологічних систем, так і для здоров'я людей. Нагальна потреба в ефективному моніторингу водних ресурсів для зменшення забруднення та забезпечення сталості цих життєво важливих екосистем ніколи не була настільки очевидною. Інтеграція технологій Інтернету речей (IoT) у моніторинг поверхневих вод трансформує підхід до вирішення цих викликів. Автоматизуючи збір та передачу даних про якість води, технології IoT дозволяють значно покращити наші здатності ефективно моніторити та впливати на стан навколишнього середовища. Ця стаття досліджує застосування різних протоколів передачі даних, включаючи Wi-Fi, Zigbee, LoRa, NB-IoT та BLE, в контексті систем моніторингу водних ресурсів, адже саме вони визначають її головні характеристики. Особлива увага була приділена визначенню фізичних умов експлуатації та обмежень, які вони накладають на функціонування систем моніторингу води. Кожен протокол розглядається з точки зору його потенційних переваг та обмежень у енергоефективності, дальності передачі, пропускної здатності та надійності в специфічних умовах експлуатації. Порівняльний аналіз у дослідженні виокремлює особливості кожного протоколу, оцінює їх придатність і пропонує методику вибору оптимальної технології для систем моніторингу води, засновану на їхніх потребах. Висновки цього дослідження підкреслюють критичну роль технологій IoT у розвитку моніторингу навколишнього середовища та виокремлюють потенційні напрямки покращень таких систем. Результатом дослідження стало визначення найбільш придатних протоколів передачі даних для розглянутих систем моніторингу.

Ключові слова: IoT; моніторинг води; LoRa; Zigbee; NB-IoT; Wi-Fi; BLE; Bluetooth.

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