Sustainable production: leveraging energy-efficient data exchange protocols

Timur Yumalin*, *Renat* Salikhov, and *Timur* Salikhov

Ufa University of Science and Technology, 450076 Ufa, Russia

Abstract. With the increasing focus on sustainability and environmental conservation, the application of Information Technology (IT) in ecology and natural resource management has become paramount. This article explores the utilization of wireless monitoring systems for sustainable production, emphasizing the importance of energy-efficient data exchange protocols. The comparison of popular energy-efficient protocols such as Bluetooth Low Energy (BLE), LoRaWAN is a focal point. The role of these protocols in optimizing data transmission while minimizing energy consumption is examined, alongside their efficacy in diverse environmental and production monitoring scenarios. Additionally, the article delves into the deployment of various sensors for monitoring production processes and environmental parameters. By analyzing real-world applications and advancements, this article aims to provide insights into the evolving landscape of wireless monitoring technology and its potential contributions to eco-friendly production practices and natural resource management.

1 Introduction

In the face of escalating environmental challenges, such as climate change, biodiversity loss, and pollution, the imperative for innovative solutions has never been more pressing. Traditional approaches to ecological and natural resource management are increasingly proving inadequate in addressing the complexities of modern environmental threats. In this context, the integration of Information Technology (IT) into environmental conservation practices offers a promising pathway forward.

The advent of the Internet of Things (IoT) represents a paradigm shift in environmental monitoring and management [1-3]. IoT systems leverage interconnected networks of sensors, actuators, and other devices to collect, transmit, and analyze real-time data from the natural world. This enables stakeholders to gain unprecedented insights into environmental dynamics and make informed decisions to mitigate negative impacts.

Crucially, the evolution of fifth-generation (5G) networks has catalyzed the expansion of IoT capabilities. 5G networks provide faster data transmission speeds, lower latency, and greater bandwidth, enabling the seamless integration of IoT devices across diverse environments. This enhanced connectivity facilitates more robust and responsive environmental monitoring systems, capable of detecting and responding to changes with greater precision and efficiency.

* Corresponding author: timur-sibay@mail.ru

Moreover, the development of energy-efficient data exchange protocols has emerged as a critical enabler of sustainable IoT deployments. Protocols such as Bluetooth Low Energy (BLE), LoRaWAN optimize data transmission while minimizing energy consumption, thereby extending the battery life of IoT devices and reducing environmental impact. By leveraging these protocols, organizations can deploy wireless monitoring systems in remote or inaccessible locations, expanding the scope of environmental monitoring efforts.

In parallel, the broader advancement of IT infrastructure and computational tools provides invaluable support for environmental conservation initiatives. Advanced modeling and simulation techniques enable researchers to predict the impacts of environmental changes and assess the effectiveness of mitigation strategies. Data-driven analytics and decision support systems empower stakeholders to optimize resource allocation, identify emerging risks, and devise evidence-based solutions to environmental challenges.

Against this backdrop, this article aims to explore the application of wireless monitoring systems for sustainable production. Specifically, we will examine the comparative advantages of energy-efficient data exchange protocols, such as BLE, LoRaWAN, in promoting eco-friendly production practices and enhancing natural resource management strategies. By delving into real-world case studies and emerging trends, we seek to elucidate the transformative potential of IT innovations in fostering environmental sustainability and resilience.

2 The role of wireless monitoring systems in production control

Wireless monitoring systems play a pivotal role in modern production control, offering a range of benefits that contribute to efficiency, sustainability, and environmental compliance. These systems utilize wireless communication technologies to remotely collect data from various sensors deployed throughout production facilities [4-6]. By providing real-time insights into key parameters and processes, wireless monitoring systems empower organizations to optimize operations, minimize downtime, and reduce environmental impact.

1. Enhanced Visibility and Control:

Wireless monitoring systems provide real-time visibility into production processes, enabling managers to monitor performance, identify bottlenecks, and make data-driven decisions. For example, in a manufacturing plant, sensors deployed on machinery can continuously monitor variables such as temperature, pressure, and vibration. This data can be analyzed to predict equipment failures before they occur, allowing for proactive maintenance and minimizing costly downtime.

2. Environmental Monitoring and Compliance:

Wireless monitoring systems facilitate continuous monitoring of environmental parameters, ensuring compliance with regulatory requirements and minimizing the risk of environmental incidents. For instance, in industries with stringent emissions regulations, such as power generation or chemical manufacturing, wireless sensors can monitor air quality, pollutant levels, and noise emissions in real time. This enables proactive measures to mitigate environmental impact and avoid costly fines.

3. Resource Optimization:

By providing granular insights into resource utilization, wireless monitoring systems enable organizations to optimize energy, water, and raw material consumption. For example, sensors installed in HVAC systems can monitor temperature, humidity, and occupancy levels to optimize energy usage and minimize waste. Similarly, in agriculture, wireless soil moisture sensors can optimize irrigation scheduling, conserving water and enhancing crop yields.

4. Remote Monitoring and Management:

Wireless monitoring systems enable remote monitoring and management of production facilities, reducing the need for on-site personnel and increasing operational flexibility. For instance, in the oil and gas industry, wireless sensors installed on offshore platforms can monitor equipment performance and environmental conditions in real time, allowing operators to respond quickly to emergencies and optimize production processes remotely.

5. Scalability and Flexibility:

Wireless monitoring systems offer scalability and flexibility, allowing organizations to easily expand monitoring capabilities as needed. Whether adding new sensors to existing infrastructure or deploying monitoring systems in remote locations, wireless technology offers unparalleled flexibility. For example, in the agriculture sector, wireless sensor networks can be deployed across vast fields to monitor soil conditions, crop health, and weather patterns, enabling precision agriculture practices.

A diagram comparing working distances and technologies of BLE and LoraWAN is shown in Figure 1.

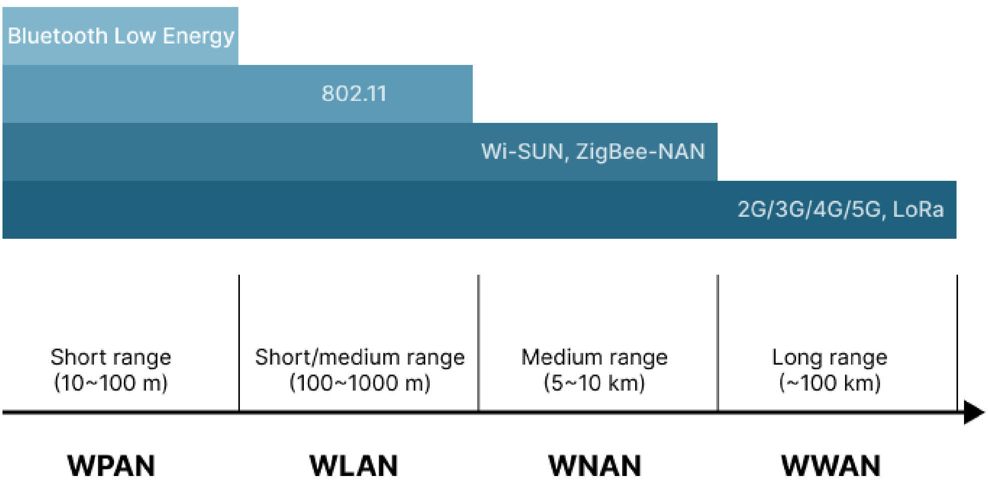

Fig. 1. BLE and LoraWAN operating ranges.

In summary, wireless monitoring systems are indispensable tools for modern production control, offering enhanced visibility, environmental compliance, resource optimization, remote monitoring capabilities, and scalability. Through real-time data collection and analysis, these systems empower organizations to improve operational efficiency, minimize environmental impact, and maintain regulatory compliance in an increasingly complex and competitive landscape.

3 Energy-efficient data exchange protocols

3.1 LoRaWAN

LoRaWAN, renowned for its long-range connectivity and energy-efficient operation, is a wireless communication protocol developed specifically for IoT and M2M applications. It offers a compelling solution for wireless monitoring systems requiring extended battery life and reliable data transmission over long distances [7-10]. Operating in the unlicensed spectrum, it enables widespread deployment without costly licensing fees. Its long-range communication capabilities make it suitable for applications spanning large geographic areas. Adopting a star-of-stars network topology, end-devices communicate with gateways that relay data to a central network server, enabling scalable deployments with minimal infrastructure requirements [11-17].

Key Features:

- Low Power Consumption: One of its most significant advantages is its energy-efficient operation, allowing devices to operate on battery power for extended periods. Devices typically consume minimal power during both transmission and idle states, enabling long battery life.

- Adaptive Data Rate: Employing adaptive data rate (ADR) mechanisms, devices dynamically adjust their data transmission rates based on signal strength and environmental conditions, ensuring efficient use of bandwidth and conserving energy.

- Sleep Modes: Devices can operate in low-power sleep modes for extended periods, waking up periodically to transmit data or respond to commands, minimizing energy consumption and extending battery life, enabling autonomous operation in remote or off-grid locations.

Widely utilized in environmental monitoring applications, it enables real-time insights into environmental conditions. In agriculture, it facilitates precision farming practices by enabling real-time monitoring of various parameters. Asset tracking solutions offer real-time visibility into the location and status of assets across wide geographic areas with minimal energy consumption.

By leveraging its energy-efficient operation, organizations can deploy robust and scalable IoT solutions for various applications, ranging from environmental monitoring to smart cities. Its low power consumption, long-range connectivity, and adaptive data rate mechanisms make it an ideal choice for wireless monitoring systems requiring extended battery life and reliable communication over large distances. A schematic diagram of the protocol principle is shown in Figure 2.

Fig. 2. LoraWAN interaction priciple diagram.

LoRaWAN has established itself as a versatile technology with a wide range of applications across various industries, offering a unique combination of long-range communication, low power consumption, reliability, scalability, and security. Here are some compelling examples of its implementation across diverse sectors:

The city of Amsterdam (Netherlands) has deployed a network to monitor and manage its extensive network of streetlights, resulting in significant energy savings and improved lighting efficiency. The city of San Diego (USA) is using it to collect data on parking occupancy, noise levels, and air quality, improving traffic management, reducing noise pollution, and protecting public health.

Emerging as a compelling technology for IoT applications, it offers a unique combination of long range, low power consumption, reliability, scalability, and security. With its growing ecosystem of devices and gateways, it continues to drive innovation across various industries.

3.2 Bluetooth low energy

Bluetooth Low Energy (BLE) is a wireless communication protocol designed for short-range data exchange with low power consumption. Originally introduced as part of the Bluetooth 4.0 specification, BLE has gained widespread adoption across various industries for its energy-efficient operation and compatibility with smartphones, tablets, and IoT devices. BLE operates in the 2.4 GHz ISM band and is characterized by its low power consumption, making it suitable for battery-powered devices and applications requiring periodic data transmission [18]. Unlike classic Bluetooth, which is optimized for high-speed data transfer over short distances, it focuses on low-power communication, enabling devices to maintain connections while conserving energy [19-20]. Devices operate in one of two modes: peripheral or central. Peripheral devices advertise their presence and can be discovered by central devices, which initiate connections and exchange data with them [21].

Key Features:

- Low Power Consumption: Minimal power consumption during both idle and active states, ideal for battery-powered applications requiring long-term operation. Devices can enter low-power sleep modes between transmissions, extending battery life.
- Fast Connection Establishment: Offers quick connection establishment times, typically within milliseconds, enabling rapid data exchange between devices. Advantageous for applications requiring rapid response times, such as proximity sensing or device control.
- Security: Incorporates robust security features, including encryption and authentication mechanisms, to protect data transmission and prevent unauthorized access. Ensures the confidentiality and integrity of exchanged data.

A schematic diagram of the BLE protocol principle is shown in Figure 3.

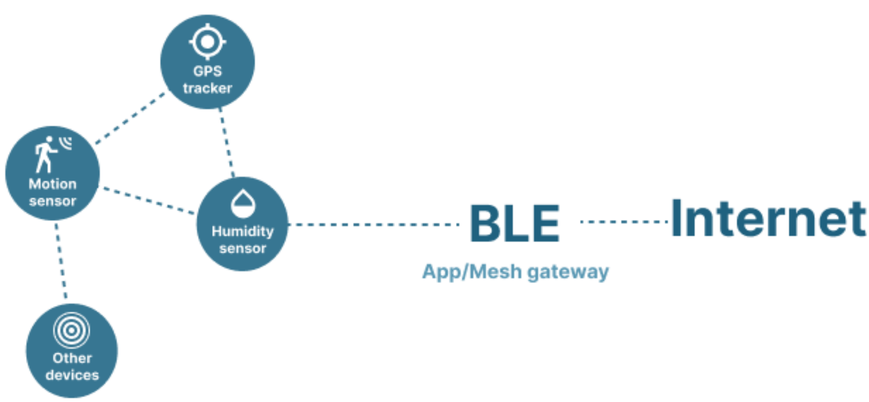

Fig. 3. BLE interaction priciple diagram.

Beacons are commonly used for indoor positioning and navigation applications, such as asset tracking, wayfinding, and proximity marketing. By deploying them throughout indoor environments, organizations can provide location-based services and personalized experiences. Wearables collect and transmit data, such as heart rate, activity levels, and sleep patterns, to smartphones or cloud-based platforms for analysis, enabling real-time health metrics tracking and remote monitoring by healthcare professionals. Home and IoT: It is foundational in smart home and IoT ecosystems, enabling wireless communication between various devices. It can be easily integrated into existing home automation systems, providing users with remote control and monitoring capabilities.

By leveraging its low power consumption, fast connection establishment, and compatibility with smartphones and IoT devices, organizations can deploy energy-efficient wireless monitoring solutions across various applications, including indoor positioning, healthcare monitoring, and smart home automation. Its simplicity, interoperability, and security features make it a versatile choice for developers and manufacturers seeking reliable and efficient wireless communication solutions.

4 Comparative analysis of LoRaWAN and Bluetooth low energy

In the realm of energy-efficient data exchange protocols for wireless monitoring systems, the comparison between LoRaWAN and Bluetooth Low Energy (BLE) emerges as a critical consideration. Both protocols offer unique advantages and features tailored to specific use cases and environments. Let's delve deeper into their comparative analysis, examining their strengths, weaknesses, and application scenarios.

LoRaWAN boasts long-range communication capabilities, making it well-suited for applications requiring data transmission over vast distances. This feature renders it particularly useful in scenarios such as environmental monitoring in remote or rural areas. Additionally, LoRaWAN devices exhibit low power consumption during both transmission and idle states, enabling prolonged battery life and autonomous operation in off-grid locations. Its scalability, facilitated by the star-of-stars network topology, further enhances its suitability for large-scale deployments spanning wide geographic areas.

Conversely, Bluetooth Low Energy excels in short-range communication applications, ideal for scenarios where devices need to exchange data over relatively small distances. BLE's rapid connection establishment times are advantageous in applications requiring low latency and real-time responsiveness, such as indoor positioning and smart home automation. Furthermore, its compatibility with smartphones, tablets, and various IoT devices simplifies integration into existing ecosystems, fostering seamless connectivity between devices.

In considering application scenarios, LoRaWAN finds its niche in environments requiring long-range communication and minimal power consumption, such as environmental monitoring, precision agriculture, and asset tracking in remote areas. On the other hand, BLE shines in short-range applications necessitating fast data exchange and compatibility with a wide range of devices, such as indoor positioning, healthcare monitoring, and smart home automation.

Despite their respective strengths, it's essential to acknowledge some considerations. While LoRaWAN offers scalability and long-range communication, its data rates may be limited compared to BLE, which excels in short-range, high-throughput applications. Conversely, BLE's effectiveness diminishes over long distances or in environments with obstacles hindering signal propagation, making it less suitable for certain outdoor or rural applications.

In conclusion, the choice between LoRaWAN and Bluetooth Low Energy (BLE) hinges on the specific requirements of the application, including communication range, power consumption, data rate, and compatibility. By carefully evaluating these factors and considering the intended use case, organizations can select the most suitable protocol for their wireless monitoring systems, ensuring optimal performance and efficiency across diverse environments.

4 Potential applications of LoRaWAN and Bluetooth low energy in ecology and natural resource management

Wireless monitoring systems powered by LoRaWAN and Bluetooth Low Energy (BLE) present a wealth of potential applications in ecology and natural resource management. These technologies offer innovative solutions to pressing environmental challenges, promising to revolutionize the way we monitor, manage, and conserve natural resources [22-24]. Let's explore some potential scenarios where these technologies can make a significant impact:

1. Environmental Monitoring:

- Both technologies can be utilized for real-time environmental monitoring, including air and water quality monitoring, soil health assessment, and biodiversity monitoring. By deploying sensors equipped with these technologies, researchers and conservationists can collect comprehensive data on environmental parameters, facilitating informed decision-making and timely interventions to mitigate pollution, habitat degradation, and ecological disturbances.

2. Precision Agriculture:

- In agriculture, they enable precision farming practices, allowing farmers to monitor soil moisture levels, temperature, humidity, and crop health in real time. This data-driven approach enables optimized irrigation scheduling, precision application of fertilizers and pesticides, and enhanced crop yields while minimizing resource usage and environmental impact.

3. Wildlife Tracking and Conservation:

- LoRaWAN and BLE-based tracking devices offer valuable tools for wildlife conservation efforts, enabling researchers to monitor animal movements, behavior, and habitat usage. By tagging animals with these devices, scientists can gather crucial data on species migration patterns, population dynamics, and interactions with human activities, informing conservation strategies and mitigating human-wildlife conflicts.

4. Smart Resource Management:

- Integrated with IoT platforms, they facilitate smart resource management initiatives, including smart water management, waste management, and energy efficiency programs. By deploying sensors and actuators in critical infrastructure systems, such as water treatment plants, waste facilities, and energy grids, municipalities and organizations can optimize resource allocation, reduce operational costs, and minimize environmental impact.

Integration of LoRaWAN and BLE technologies with advanced data analytics, artificial intelligence, and machine learning algorithms holds the promise of unlocking new insights into complex ecological systems and natural resource dynamics. Predictive modeling, anomaly detection, and decision support systems can help forecast environmental trends, identify emerging risks, and develop proactive strategies for sustainable management and conservation. The scalability, low power consumption, and compatibility of LoRaWAN and BLE technologies offer significant advantages in remote and resource-constrained environments, where traditional monitoring methods may be impractical or costly. From remote wilderness areas to urban green spaces, these technologies enable continuous monitoring and management of natural resources, empowering stakeholders to address environmental challenges with greater precision and efficiency.

Despite their potential, the widespread adoption of this technologies in ecology and natural resource management faces several challenges, including data security and privacy concerns, interoperability issues, and regulatory hurdles. Addressing these challenges requires collaboration among stakeholders, including governments, academia, industry, and civil society, to develop standardized protocols, best practices, and regulatory frameworks. Looking ahead, the continued innovation and evolution of this technologies hold immense promise for advancing environmental conservation, sustainable agriculture, and natural resource management. As these technologies become more sophisticated and ubiquitous, they have the potential to drive transformative change, ushering in a new era of ecological stewardship and resilience.

In conclusion, LoRaWAN and Bluetooth Low Energy technologies offer vast potential for addressing environmental challenges and managing natural resources more sustainably. By harnessing the power of wireless monitoring systems, integrated with advanced data analytics and decision support tools, we can unlock new opportunities for innovation, collaboration, and conservation, paving the way for a more resilient and environmentally sustainable future.

5 Conclusion

In the realm of energy-efficient data exchange protocols, LoRaWAN and Bluetooth Low Energy (BLE) stand out as versatile solutions with unique strengths and applications. LoRaWAN, recognized for its long-range connectivity and low power consumption, excels in scenarios requiring extended battery life and reliable transmission over vast distances. Its adoption in environmental monitoring, precision agriculture, and asset tracking demonstrates its effectiveness in diverse applications, offering scalability, reliability, and security.

Conversely, BLE is tailored for short-range communication with fast connection establishment times and minimal power consumption. Its compatibility with smartphones, wearables, and IoT devices makes it ideal for indoor positioning, healthcare monitoring, and smart home automation. BLE's versatility and ease of integration contribute to its widespread adoption across various industries.

When considering the choice between LoRaWAN and BLE for wireless monitoring systems, organizations must evaluate factors such as communication range, power consumption, and data rate requirements. By selecting the most suitable protocol for their specific use case, organizations can maximize performance and efficiency while addressing environmental challenges and managing natural resources sustainably. As these technologies continue to evolve and innovate, collaboration among stakeholders will be crucial in overcoming challenges such as data security, interoperability, and regulatory compliance. By leveraging advanced data analytics and machine learning algorithms, LoRaWAN and BLE have the potential to unlock new insights into ecological systems, driving transformative change and ushering in a more resilient and environmentally sustainable future.

In conclusion, the combination of LoRaWAN and Bluetooth Low Energy technologies offers vast potential for innovation, collaboration, and conservation, paving the way for a more sustainable and resilient future in ecology and natural resource management.

The research was funded with the support of a state assignment (scientific code FZWU-2023-0002)

References

1. A. A. Laghari, K. Wu, R. A. Laghari, M. Ali, A. A. Khan, Arch. Comput. Methods Eng., 1-19 (2021)
2. T. T. Yumalin, R. B. Salikhov, V. Kh. Abdrakhmanov, T. R. Salikhov, K. V. Vazhdaev, T. D. Muntyanova, Petroleum Engineering **21(3)**, 232-242 (2023)
3. R. B. Salikhov, V. K. Abdrakhmanov, T. T. Yumalin, “Experience of Using Bluetooth Low Energy to Develop a Sensor Data Exchange System Based on the NRF52832

Microcontroller", in *2021 International Ural Conference on Electrical Power Engineering (UralCon)*, IEEE, Magnitogorsk, Russia (2021)

4. T. R. Salikhov, V. K. Abdrakhmanov, T. T. Yumalin, "Application of Organic Sensors in Wireless Environmental Monitoring Systems", in *2021 International Conference on Electrotechnical Complexes and Systems (ICOECS)*, IEEE, Ufa, Russia (2021)
5. T. T. Yumalin, R. B. Salikhov, T. R. Salikhov, "Integrating Wireless Sensor Networks with Organic Polymers for Sustainable", in *Hydraulic and Civil Engineering Technology* **VIII** (2023)
6. T. T. Yumalin, T. R. Salikhov, A. A. Gaskarova, E3S Web Conf. **443**, 06004 (2023)
7. S. Okur, Chemosensors **9**, 2 (2021)
8. Y. Shifeng, K. E. Jing, Z. Jimin, "Wireless monitoring system for aquiculture environment", in *2007 IEEE International Workshop on Radio-Frequency Integration Technology* (2007)
9. F. Viani, M. Bertolli, M. Salucci, A. Polo, IEEE sensors journal **17(13)**, 4299-4309 (2017)
10. R. R. Sharma, JSCP **3**, 3 (2021)
11. H. Kopetz, W. Steine, *Cham: Springer International Publishing* (2022)
12. C. Liu, Y. Zhang, H. Zhou, J. Phys. Conf. Ser. **2093**, 1 (2021)
13. A. Lacava, Comput. Netw. **211** (2022)
14. S. M. Darroudi, R. Caldera-Sànchez, C. Gomez, Sensors **19**, 5 (2019)
15. R. Katila, T. N. Gia, T. Westerlund, Comput. Netw. **209**, (2022)
16. R. A. Karalash, T. G. Korotkova, Scientific works of KubSTU **7**, 314-324 (2019)
17. J. Haxhibeqiri, E. De Poorter, I. Moerman, J. Hoebeke. Sensors **18(11)**, 3995 (2018)
18. F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, T. Watteyne, IEEE Commun. Mag. **55(9)**, 34-40 (2017)
19. M. A. Almuhaya, W. A. Jabbar, N. Sulaiman, S. Abdulmalek, Electronics **11(1)**, 164 (2022)
20. R. N. Gore, H. Kour, M. Gandhi, D. Tandur, A. Varghese, "Bluetooth based sensor monitoring in industrial iot plants", in *2019 International Conference on Data Science and Communication (IconDSC)* (2019)
21. J. Hughes, J. Yan, K. Soga. Int. J.Intell. Syst. **8(2)**, 1379-1405 (2015)
22. N. E. Guevara, Y. H. Bolaños, J. P. Diago, J. M. Segura, HardwareX **12**, e00330, (2022)
23. M. R. Ghori, T. C. Wan, G. C. Sodhy,Sensors **20(12)**, 3590 (2020)
24. S. Bagwari, A. Gehlot, R. Singh, N. Priyadarshi, B. Khan, IEEE Access **10**, 7107-7127 (2021)