ANNOTATION

to the dissertation work (series of articles) submitted for the degree of Doctor of Philosophy (PhD) in the educational program «8D06201–Radioengineering, electronics and telecommunications»

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IMPROVING NODE LOCALIZATION ACCURACY AND DATA TRANSMISSION EFFICIENCY IN WIRELESS SENSOR NETWORKS USING MACHINE LEARNING

General characteristics of the work

The dissertation (series of articles) is devoted to improving the localization accuracy of nodes in wireless sensor networks (WSNs) based on Long Range (LoRa) technology using machine learning methods and numerical modeling, as well as enhancing data transmission efficiency in Long Range Wide Area Network (LoRaWAN) systems through the application of reinforcement learning methods for optimizing transmission parameters under high node density conditions.

Relevance of the topic

The modern development of the Internet of Things (IoT), Smart cities, and Smart buildings has led to the widespread deployment of WSNs, which are used for real-time monitoring, control, and management of various objects. The operational efficiency of WSNs is largely determined by several factors, among which the most critical are the accuracy of sensor node localization, the reliability of data transmission, and the energy efficiency of devices. These factors directly influence the performance quality of monitoring and control systems in such fields as industry, transportation, medicine, logistics, and smart-building infrastructure.

One of the most complex and in-demand tasks in WSNs is indoor node localization. Existing traditional localization methods have several significant limitations. Geometric approaches based on time- and angle-related signal characteristics require expensive equipment, complex synchronization, and high-precision measurement systems, which restrict their applicability in large-scale deployments. Moreover, satellite navigation systems such as GPS - widely used outdoors - are ineffective indoors, as signals are severely attenuated by walls, floors, and engineering structures, making coordinate determination impossible or extremely inaccurate. In contrast, the fingerprinting method based on the Received Signal Strength Indicator (RSSI) is more practical and accurate, as it relies on experimentally collected radio maps that reflect real environmental conditions such as room layout, construction materials, partitions, and interference sources. This allows the method to significantly improve localization accuracy. However, the fingerprinting approach is associated with high labor intensity when constructing radio maps, the need for frequent database updates, and sensitivity to environmental changes, which reduces its scalability and universality. Consequently, there is a need

for new approaches that can simultaneously improve localization accuracy and reduce data collection costs.

A particularly important task is improving the energy efficiency and robustness of data transmission in LoRaWAN networks, which in recent years have been considered one of the most promising technologies for large-scale sensor systems. However, in urban environments - characterized by dense buildings, interference, and a high number of nodes - the effectiveness of the standard Adaptive Data Rate (ADR) mechanism decreases. This leads to a reduction in packet delivery ratio, an increase in data loss probability, and higher energy consumption due to repeated transmissions. As a result, not only does the network's reliability degrade, but its scalability also suffers, since performance declines significantly as the number of devices grows. Therefore, there is a practical need to introduce advanced transmission-parameter optimization methods that can enhance the robustness and energy efficiency of LoRaWAN networks under real urban-infrastructure conditions.

Thus, the relevance of this research is defined by the need to develop and apply new approaches that combine machine learning methods, numerical modeling, and reinforcement learning algorithms to improve indoor node localization accuracy and data transmission efficiency in WSNs under urban conditions. Solving these problems is essential for the further advancement of IoT technologies, Smart cities, and modern telecommunication systems.

The purpose of the research. Improving localization accuracy using machine learning methods and enhancing data transmission efficiency by applying reinforcement learning algorithms based on the optimal selection of transmission parameters in LoRaWAN networks.

To achieve the stated purpose, the following tasks must be accomplished:

- to model signal propagation and investigate the influence of parameters obtained from numerical modeling on the accuracy of the radio map construction model;
- to study the application of transfer learning for constructing an RSSI-based radio map in new indoor environments with a reduced amount of experimental data and to evaluate the impact of this approach on localization accuracy;
- to investigate methods for the optimal selection of LoRaWAN transmission parameters based on reinforcement learning algorithms and to compare their effectiveness with other reinforcement learning algorithms and with the standard ADR mechanism in terms of packet delivery ratio and energy consumption.

Research methods:

- modeling of signal propagation in the COMSOL Multiphysics environment, followed by analysis of the parameters obtained from the modeling and evaluation of their influence on the accuracy of the radio map construction model;

- application of machine learning methods (GRU, LSTM, RBFN, XGBoost, and 1D CNN) and transfer learning for constructing radio maps and determining node locations in the Python environment;
- simulation modeling of LoRaWAN operation in the NS-3 environment using reinforcement learning algorithms to optimize transmission parameters, followed by comparison of their effectiveness with the standard ADR mechanism and alternative reinforcement learning algorithms.

Object of the research. Wireless sensor networks based on LoRa technology.

Subject of the research. Localization accuracy of LoRa nodes, machine learning methods, reinforcement learning algorithms, data-transmission efficiency in wireless sensor networks, and LoRaWAN transmission parameters.

The scientific novelty of the work lies in the fact that, for the first time:
- it was established that the use of the estimated distance parameter between the transmitting and receiving devices increases the accuracy of constructing the radio map of LoRa nodes compared to models based solely on RSSI data;
- the transfer learning method was applied to generate an RSSI-based radio map of LoRa nodes under scaled conditions with a reduced amount of experimental data, without significant loss of localization accuracy;;
- the reinforcement learning algorithm Double Deep Q-Network with Prioritized Experience Replay (DDQN-PER) was employed for the optimal selection of LoRaWAN transmission parameters with the aim of increasing the packet delivery ratio.

Provisions for the defense:
1. The use of the estimated distance between the transmitter and the receiver, obtained through signal propagation modeling, in machine learning for radio map construction increases the model accuracy by 3.7%.
2. The transfer learning method generates a complete RSSI radio map using only 20% of the experimental data while maintaining localization accuracy above 91%.
3. The Double Deep Q-Network with Prioritized Experience Replay (DDQN-PER) algorithm for selecting optimal transmission parameters in LoRaWAN provides a 17.2% improvement in packet delivery ratio compared to the standard Adaptive Data Rate (ADR) mechanism.

Scientific and practical significance of the work. The results of the study can be used in the design and deployment of indoor positioning systems and wireless sensor networks in modern IoT solutions. The proposed radio map construction approaches using transfer learning significantly reduce the labor intensity of data collection and decrease the dependence of localization systems on specific building characteristics, enabling easier scalability and deployment of technologies in new buildings and infrastructure facilities. The reinforcement learning‑based algorithm

for optimizing LoRaWAN transmission parameters enhances network robustness under high node density by reducing packet loss and lowering device energy consumption. The obtained results may be in demand for the development of intelligent building management systems, industrial monitoring platforms, and logistics solutions, as well as contribute to reducing operational costs and extending the service life of sensor devices.

Reliability and validity of the obtained results. The reliability of the results is confirmed by publications in international scientific journals indexed in major global databases with high impact factors.

Author's personal contribution. The formulation of research tasks, adjustment of methodological approaches, and discussion of scientific results were carried out jointly with the academic supervisors. The author performed all stages of the study, including the development and modeling of radio maps based on RSSI, the implementation of the transfer learning approach, as well as numerical modeling of signal propagation in the COMSOL Multiphysics environment. Data processing and the implementation of machine learning algorithms for evaluating localization accuracy were carried out by the author in the Python environment. The simulation modeling of LoRaWAN network operation under high node density was conducted in the NS-3 environment, and a reinforcement learning algorithm was applied to optimize the transmission parameters. The author analyzed the obtained results, compared them with existing methods, and prepared the corresponding conclusions.

Approbation of the work. The results of the dissertation (series of articles) have been published in the following sources:

Articles published in journals indexed in international scientific databases such as Thomson Reuters and Scopus:

1. **Zholamanov B.,** Saymbetov A., Nurgaliyev M., Orynbassar S., Dosymbetova G., Kapparova A., Kuttybay N., Koshkarbay N., Yershov E., Bolatbek A., Kopbay K. Indoor localization of LoRa wireless modules based on RSSI fingerprint method using transfer learning // Results in Engineering – 2025. – V. 28. – P. 108383. **Web of Science: Impact Factor 7.9, Q1. Scopus: CiteScore 8.2, Percentile 86%.** https://doi.org/10.1016/j.rineng.2025.108383
2. **Zholamanov B.,** Bolatbek A., Saymbetov A., Nurgaliyev M., Yershov E., Kopbay K., Orynbassar S., Dosymbetova G., Kapparova A., Kuttybay N., Koshkarbay N. Enhanced Reinforcement Learning Algorithm Based-Transmission Parameter Selection for Optimization of Energy Consumption and Packet Delivery Ratio in LoRa Wireless Networks // Journal of Sensor and Actuator Networks. – 2024. – V. 13. – № 6. – P. 89. **Web of Science: Impact Factor 4.2, Q2; Scopus: CiteScore 9.7, Percentile 95%.** https://doi.org/10.3390/jsan13060089
3. **Zholamanov B.,** Saymbetov A., Nurgaliyev M., Bolatbek A., Dosymbetova G., Kuttybay N., Orynbassar S., Kapparova A., Koshkarbay N., Beyca Ö. F. RSSI Fingerprint-Based Indoor Localization Solutions Using Machine Learning Algorithms: A Comprehensive Review // Smart Cities. – 2025. – V. 8. – № 5. – P.

153. **Web of Science: Impact Factor 5.5, Q1. Scopus: CiteScore 14.7, Percentile 95%.** https://doi.org/10.3390/smartcities8050153

Scientific articles published in journals recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education

1. Bolatbek A.B., **Zholamanov B.N.,** Nurgaliyev M.K., Saymbetov A.K., Abzhanova G.M. ENERGY EFFICIENT ALGORITHM FOR TRANSMISSION PARAMETER SELECTION IN LORA WIRELESS NETWORKS // Bulletin of D. Serikbayev EKTU. – 2025. – Т. 1. – №3. – С. 157. https://doi.org/10.51885/1561-4212_2025_3_157

Zholamanov B.N., Saymbetov A.K., Nurgaliyev M.K., Bolatbek A.B. Indoor positioning system for LoRa nodes based on the RSSI fingerprint method using transfer learning. Republic of Kazakhstan, «National Institute of Intellectual Property», 2025, Certificate of Copyright No. 64965 dated December 4, 2025.

Relation of the dissertation topic to research program plans

The dissertation work (series of articles) was partially carried out in accordance with the research plan of the scientific project "Improving the energy efficiency of mobile and static wireless sensor nodes in indoors and outdoors" for the years 2023‑2025, individual registration number (IRN) AP19678552.