Institute of Theoretical and Applied Informatics
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DOCTORAL DISSERTATION SUMMARY

The selection of relay node locations in a LoRa network and their impact on network efficiency

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Summary

One of the key challenges in LPWAN networks is the problem of areas in the network where the coverage is limited, i.e. places where devices are unable to communicate effectively with the network. A feasible solution to this problem is the use of relay nodes, which can collect data from neighboring nodes and forward these signals to the access point, enabling nodes with poor connectivity with the network to remain connected effectively. The use of relay nodes in LPWAN networks opens up new research areas because, so far, transmissions in these standards have only been carried out directly between the end node and the access point. In 2022, the LoRa Alliance published the official relay functionality specification for LoRaWAN, specifying how relay devices operate, but not answering the question of where physical relay devices should be installed in order to maximize energy efficiency in the LoRa network, which is important in the context of using battery–powered devices in IoT applications using LPWAN technology. The importance of the research problem goes beyond theoretical analysis, reflecting a robust practical justification. The topic of relay usage for the LoRaWAN standard – a still developing technology – is the subject of discussion in relevant standardization organizations such as LoRa Alliance, which is an additional motivation for the research conducted in this dissertation.

This dissertation aims to develop methods for selecting the locations of relay nodes in a LoRa network to optimize its energy efficiency. Based on the analysis of the stated research problem and the results of the studies conducted in this dissertation, the following thesis has been confirmed:

The appropriate selection of relay node locations in a LoRa network improves the network's energy efficiency.

To confirm the thesis, the dissertation focuses on developing new methods for selecting the locations of relay nodes in a LoRa network, including a set of procedures and criteria that take into account relevant parameters (such as the SF or the battery level of the device), as well as the characteristics of the LoRa technology environment (e.g., variability in radio signal propagation conditions). The proposed methods are optimized to provide the network's energy efficiency. As a result, the network operating in the configuration recommended by the algorithm is expected to exhibit energy-efficient resource usage and minimal energy consumption.

At the beginning of the work on the research problem, an analysis of data from large–scale commercial IoT deployments was conducted, allowing for the assessment of whether and under what circumstances there is potential for

the use of relay nodes in real–life network operations. The results of the analyses indicate the presence of limited network connectivity for a certain percentage of the network's nodes and that addressing this issue through the deployment of relay nodes in appropriate locations is justified and represents an effective alternative to other methods of covering network blind spots, such as expanding the infrastructure by installing additional LoRa gateways. Furthermore, the analyses' results align with Semtech Corporation's expertise and assumptions, as it is a leader in the development and provision of LoRa technology.

The dissertation proposes new goal functions for optimization procedures where the primary resource being optimized is energy. An important aspect is considering energy consumption constraints in nodes due to their battery–powered operation. The energy required for relaying packets by a relay node can shorten its remaining operational time, thus reducing its originally predicted lifespan.

In the early stages of work, selecting relay node locations was considered a graph assignment problem. As a solution, a heuristic approach was proposed, which serves as an alternative to exact methods in the case of sparse graphs. Simulation experiments indicate that the proposed approach demonstrates higher efficiency in maximizing network lifetime compared to the reference method. The reference method used was an implementation of an algorithm that optimizes relay node selection in terms of minimizing energy consumption, which considers multiple nodes with limited network connectivity and multiple potential relay nodes, similar to the considerations in this dissertation.

In the next stage of the work, the focus is on developing a more comprehensive solution based on a greedy approach. The proposed method not only addresses previously identified challenges but also includes a new mechanism designed for cyclic execution, allowing for periodic reconfiguration of the network in response to changing radio signal propagation conditions. Furthermore, the developed method avoids unnecessary excess in the number of nodes selected to operate in relay mode. In the final stage of the work, the generalization of the relay nodes' location selection problem was considered, taking into account the redundancy constraint. Based on the developed greedy method, an approach was proposed to find a set of relay node locations, ensuring that each node with limited network connectivity is within range of a specified number of relay nodes defined by a redundancy factor. This approach contributes to increased network reliability in the event of relay device failures.

In the methods' evaluation process, a custom–designed evaluation environment was used to assess the effectiveness of relay nodes' location selection methods. This environment utilized the implementation of a simulation model in the OMNeT++ discrete event simulator. The simulation experiment scenarios included both random node distribution topologies and those based on real–life IoT deployments. The simulation results indicate that the proposed approach enables the identification of intermediary nodes that ensure network operation for a specified period, reducing the risk of operational continuity disruption due to premature battery depletion. The level of energy savings in the network achieved by the proposed greedy method ranges from 0.19% to 7.96%, depending on the network topology scenario, confirming that this algorithm achieves better results in terms of ensuring network energy efficiency compared to the reference method. The proposed algorithm demonstrates effectiveness for varying percentages of devices with poor direct network connectivity and for diverse distributions of such nodes within the network. Thus, the research results confirm the fulfilment of the dissertation objective and the stated thesis.

Published papers

Papers directly related to the dissertation:

1. A. Strzoda and K. Grochla. "A Nature-Inspired Approach to Energy-Efficient Relay Selection in Low-Power Wide-Area Networks (LPWAN)". in: *Sensors* 24.11 (2024). ISSN: 1424-8220. DOI: 10.3390/s24113348

2. K. Grochla, A. Strzoda, R. Marjasz, P. Głomb, K. Książek, and Z. Łaskarzewski. "Energy-Aware Algorithm for Assignment of Relays in LP WAN". in: *ACM Trans. Sen. Netw.* 18.4 (2022). ISSN: 1550-4859. DOI: 10.1145/3544561

3. A. Strzoda, K. Grochla, A. Frankiewicz, and Z. Łaskarzewski. "Measurements and Analysis of Large Scale LoRa Network Efficiency". In: *2022 International Wireless Communications and Mobile Computing (IWCMC)*. 2022, pp. 818–823. DOI: 10.1109/IWCMC55113.2022.9824317

Other papers:

4. A. Strzoda, R. Marjasz, and K. Grochla. "How Accurate is LoRa Positioning in Realistic Conditions?" In: *Proceedings of the 12th ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications.* DIVANet '22. Montreal, Quebec, Canada: Association for Computing Machinery, 2022, 31–35. DOI: 10.1145/3551662.3561260

5. R. Marjasz, K. Połys, A. Strzoda, and K. Grochla. "Improving Delivery Ratio in LoRa Network". In: *Proceedings of the 19th ACM International Symposium on Mobility Management and Wireless Access.* Mobi-Wac '21. Alicante, Spain: Association for Computing Machinery, 2021, 141–146. ISBN: 9781450390798. DOI: 10.1145/3479241.3486698

6. A. Strzoda, K. Grochla, P. Głomb, and A. Madej. "Link failure prediction in LoRa networks". In: *2023 International Wireless Communications and Mobile Computing (IWCMC)*. 2023, pp. 1310–1315. DOI: 10.1109/IWCMC58020.2023.10183185

7. R. Marjasz, A. Strzoda, K. Połys, and K. Grochla. "Mitigation of LoRa Interferences via Dynamic Channel Weights". In: *Proceedings of the 35th annual European Simulation and Modelling Conference ESM 2021.* 2021, pp. 150–154

8. A. Strzoda, R. Marjasz, and K. Grochla. “LoRa Positioning in Verification of Location Data’s Credibility”. In: *Infocommunications Journal* 14.4 (2022), pp. 56–61

9. A. Strzoda, K. Grochla, and K. Połys. “Variability of BLE Advertisement Packets Received Signal Strength and Delivery Probability in the Presence of Interferences”. In: *Proceedings of the 12th ACM International Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications.* 2022, pp. 37–44

10. R. Marjasz, K. Grochla, A. Strzoda, and Z. Łaskarzewski. “Simulation Analysis of Packet Delivery Probability in LoRa Networks”. In: *Computer Networks: 26th International Conference, CN 2019, Kamień Śląski, Poland, June 25–27, 2019, Proceedings 26.* Springer. 2019, pp. 86–98

11. A. Strzoda. “Zastosowanie heurystyki do wyboru lokalizacji węzłów pośredniczących w sieciach LP WAN”. in: *Przegląd Telekomunikacyjny+ Wiadomości Telekomunikacyjne* (2023)

12. K. Grochla, R. Marjasz, K. Połys, and A. Strzoda. “Kolizje pakietów w Sieciach LoRa w Zastosowaniach Smart City”. In: *Przegląd Telekomunikacyjny+ Wiadomości Telekomunikacyjne* (2019)

13. A. Frankiewicz, A. Glos, K. Grochla, Z. Łaskarzewski, J. Miszczak, K. Połys, P. Sadowski, and A. Strzoda. “LP WAN gateway location selection using modified k-dominating set algorithm”. In: *Modelling, Analysis, and Simulation of Computer and Telecommunication Systems: 28th International Symposium, MASCOTS 2020, Nice, France, November 17–19, 2020, Revised Selected Papers 28.* Springer. 2021, pp. 209–223