Institute of Theoretical and Applied Informatics
Polish Academy of Sciences

ABSTRACT OF DOCTORAL DISSERTATION

Energy Consumption Reduction in Low-Power Wide-Area Networks Through Transmission and Listening Management

Author: mgr inż. Zbigniew Łaskarzewski

Supervisor: dr hab. inż. Krzysztof Grochla, prof. IITiS PAN

Gliwice, 2025

Abstract

The development of low-power wireless communication technology has enabled the widespread deployment of Internet of Things (IoT) devices in applications such as remote meter reading, transport monitoring, industrial process supervision, and monitoring of liquid levels in tanks. Market forecasts indicate further dynamic growth in the number of such applications. However, a key challenge remains the minimization of energy consumption to ensure long-term, maintenance-free operation of battery-powered devices.

The design of IoT devices focuses on the energy efficiency of electronic components, sleep modes, and wake-up mechanisms. Of particular importance, however, is the energy efficiency of the communication protocol stack, which determines how radio transmission and listening are managed. Appropriate selection and parameterization of communication protocols have a crucial impact on the reliability, scalability, and operational lifetime of devices. Therefore, the objective of this work was to develop mechanisms for reducing the energy consumption of IoT devices at the communication protocol level, enabling at least 10 years of device operation without battery replacement while maintaining full functionality.

The work includes an analysis of radio wave propagation in LPWAN networks using well-known simulation models, as well as a large-scale measurement campaign conducted in an urban environment. The analysis focused on communication quality parameters, including bit error characteristics, packet loss rate, and, in particular, the received signal strength and its variability. This analysis made it possible to fit statistical models of fast and slow fading to the empirical data and to develop a transmission power control method with a predefined effectiveness. The applied propagation models enabled reliable prediction of path loss, confirming their usefulness in planning the placement of gateway devices.

As part of this work, an original communication protocol, BX-MAC, was proposed. The protocol employs sampled listening and introduces a novel concept of wake-up frames with a segmented preamble. This approach enables a significant reduction in the energy consumption of network nodes compared with existing solutions. Additionally, complementary mechanisms were developed, such as indicating the response delay or the next listening opportunity, which reduce the duration of response listening and enable energy-efficient broadcast transmission. Guidelines for selecting protocol parameters were formulated, and the energy consumption of devices operating as end nodes in a star topology network as well as retransmitters was estimated. The energy efficiency of the BX-MAC protocol was compared with baseline protocols, demonstrating its advantages in the analyzed scenarios.

The transmission and listening model proposed in the BX-MAC protocol was validated through the implementation of a remote gas meter reading system. Practical deployment required the development of additional energy-saving mechanisms that take into account the device architecture and the timing requirements imposed by metrological functionality. Various sampled listening models and sleep modes were analyzed, and the obtained results were verified through energy consumption measurements. A communication scheme for remote meter reading systems was also developed, using the broadcast communication capability of the BX-MAC protocol to initiate communication with end devices. The proposed communication model reduced energy consumption by 39% and accelerated the reading process by at least a factor of 1.8 compared with the commonly used periodic transmission model.

The BX-MAC protocol and the proposed mechanisms for managing transmission and listening are universal and can be applied to various wireless communication technologies. The solution is particularly energy-efficient in asynchronous communication scenarios, where maintaining time synchronization between nodes is impractical, for example in walk-by remote meter reading systems. The achieved energy efficiency enables up to ten years of uninterrupted device operation while still providing a short communication initiation time, which is required in many practical IoT applications.