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RESEARCH OF THE METHODS FOR OPTIMIZING ENERGY CONSUMPTION IN IEEE 802.15.4 PROTOCOLS

The paper investigates existing methods for optimizing energy consumption in IEEE 802.15.4 Internet of Things protocols. The following protocols were considered: ZigBee, 6LoWPAN, and WirelessHART. The ZigBee protocol has a sleep mode, frequency response control, transmitter power management, data aggregation and buffering, and transmission route optimization. 6LoWPAN uses sleep mode, frequency response control, IPv6 header compression, fragmentation and reassembly, and transmission route optimization. The WirelessHART protocol uses sleep and activation mode, frequency mesh, transmitter power management, data buffering and aggregation, transmission route optimization, and network topology management.

The study selected the criteria by which all optimization methods in IoT protocols are distributed: Device activity time management, Transmission frequency characteristics management, Transmitter power management, Data packet management, and Route management.

The ZigBee and Wireless HART protocols have optimization methods for all the proposed categories. The 6LoWPAN protocol has 4 categories of optimization methods, except for the Transmitter Power Management category.

The best energy efficiency indicators are found in the optimization methods of "Device activity time management" and "Route management." This is because devices are turned off when data is not needed to collect and transmit. Since devices can send data from other devices to the data center, the routing setting eliminates unnecessary data transfers and leaves the device in sleep mode longer instead of waiting for data from other devices to be sent. The worst-performing methods are those in the Transmission frequency management category because they are based on detecting transmissions that create collisions. Still, devices are in sleep mode most of the time, and their transmissions rarely overlap, so collisions are rare.

Key words: *Internet of Things, IEEE 802.15.4 standard, protocols, energy efficiency, optimization, devices.*

Problem statement. Extensive Internet of Things systems are built using protocols based on the IEEE 802.15.4 standard.

The IEEE 802.15.4 standard was specifically designed to design IoT systems because of its low power consumption, optimal data rate, and relatively long transmission distance [1]. Power consumption is still a significant concern for devices operating without replacing the power supply for years. Using the standard as a basis, separate protocols have been developed that implement their methods for optimizing energy consumption.

Analysis of recent research and publications. Paper [2] reviews publications on the energy efficiency of IoT protocols but does not specify the specific optimization methods used to achieve energy efficiency or provide numerical values of the optimization efficiency.

Paper [3] investigates the impact of encryption methods on energy consumption. The results only allow for the choice of an encryption method for the operation of the Internet of Things protocol but do not allow for the analysis of the impact of optimization methods on the energy efficiency of protocols.

The aim of this work is to analyze existing Internet of Things protocols based on the IEEE 802.15.4 standard concerning the energy optimization methods available in them, to systematize them by category, and to determine their impact on the overall energy efficiency of the protocol.

Presentation of the main research material. The main protocols based on the IEEE 802.15.4 standard include ZigBee, 6LoWPAN, and WirelessHART.

ZigBee is a standard network protocol for Internet of Things devices supported exclusively by the ZigBee Alliance and uses the transport services of the IEEE802.15.4 network specification [4].

ZigBee energy optimization is performed in the following ways:

– Sleep mode – there are two sleep modes: sleep mode and cyclic sleep mode.

Sleep mode is used to wake up and put the module to sleep using a hardware contact. When the contact is activated, the module enters sleep mode after completing any transmitting or receiving in progress. If the module is not connected to the network, it will enter sleep mode when connected [5].

When a connected end device wakes up from sleep mode, it sends a polling request to the base station to see if the station has buffered data for the end device. The end device will continue to send polling requests every 100 ms as long as it remains active.

Cyclic sleep allows the modules to wake up periodically to check for data from the station and sleep when inactive. In cyclic sleep mode, if serial or RF data is received, the module will start an inactivity timer and remain awake until the timer expires. While the module is awake, it will continue to send polling requests to its station to check the buffered data every 100 ms. The timer will restart whenever serial or RF data is received. The module will resume sleep mode when the timer expires.

– Data aggregation and buffering – As with other protocols, data aggregation sends multiple data frames in a single transmission. This reduces the overhead of 802.11 because numerous packets can be sent with a single header instead of each packet having its own header.

– Transmitter power management – When building a network, you can adjust the transmitter power of devices to reduce power consumption while preventing the signal from being too weak to reach the station.

– Frequency response control – Zigbee uses 16 channels (11th to 26th) in the 2.4 GHz band worldwide, 13 channels in the 915 MHz band in North America, and one channel in the 868 MHz band in Europe. Some devices also use the 784 MHz band in China for Zigbee [6].

Each Zigbee device uses a bandwidth of up to 2 MHz in these channels, while a 5 MHz guard band separates any two channels to prevent interference caused by other Zigbee devices. This avoids collision during data transmission.

– Optimization of transmission routes – ZigBee has basic network topology options: Star, Tree, and Mesh [7]. By configuring transmission routes, you can reduce the number of hops in the path or reduce or eliminate transmission through intermediate nodes in a mesh topology.

The 6LoWPAN protocol was developed based on IEEE802.15.4 to build a network based on IPv6 addressing with independent organization of routing in the network [8].

6LoWPAN energy optimization is performed in the following ways:

– Sleep mode – To reduce the energy consumption of a 6LoWPAN node, a channel access mechanism based on the node's sleep state is proposed. Its idea is that nodes can sleep appropriately during both the superframe delay and superframe sleep periods [9].

– IPv6 Header Compression – 6LoWPAN supports header compression in the IPv6 addressing system as one of its features to reduce the number of bits in the header through compression techniques [10].

HC1 was the first IPv6 header compression method for 6LoWPAN proposed in RFC 4944 in 2007. HC1 is an acronym for Header Compression 1. Instead of 40 bytes of the IPv6 header, 2 bytes indicate how the IPv6 header is compressed and where its value can be recovered during decompression [11].

A header compression technique that can compress local, global unicast, and multicast IPv6 addresses is Internet Protocol Header Compression (IPHC). This encoding can consist of 2 bytes (in local link communication) or 3 (with additional contextual encoding).

S&SFHC is an abbreviation for second and subsequent fragment header compression. This header compression method is suggested when packets need to be fragmented. Ideally, the IPv6 header should be transmitted with all fragments of the same packet. In S&SFHC, the header from the first fragment is stored in a header dictionary. The header dictionary stores a copy of the header received in the first fragment. The recipient sends an 8-bit unique link identifier (LUI) to the sender from its list of accessible unique identifiers (FUIList). The sender replaces the IPv6 header with this identifier in subsequent fragments. S&SFHC uses two approaches – standalone and integrated. In the standalone approach, the header in the first fragment is sent without any compression. In subsequent fragments, the header is replaced by the compressed S&SFHC header, i.e., the LUI, which the recipient sends. In the integrated approach, the header in the first fragment is compressed using IPHC technology, and the compressed S&SFHC header is in the following fragments.

– Fragmentation and reassembly – The existing limitations in 6LoWPAN are one of the main challenges in data aggregation techniques. However, traditional CSMA/CA at the MAC layer can cause significant transmission, control overhead, and delay during listening and channel competition. It could be more efficient to transmit an IPv6 packet because of the large packet header. The solution to this problem is to aggregate data from multiple packets into one if it does not have consequences due to data transmission delay [12].

– Frequency response control – The PHY layer specification defines how 6LoWPAN devices can communicate with each other over the wireless channel. A total of 27 channels are represented at the PHY layer. These channels are distributed in different frequency bands with varying data rates [13]. Controlling the channel allocation reduces the number of collisions that occur during data transmission. It reduces the number of retransmissions that must happen in the event of a crash during simultaneous transmission.

– Optimization of transmission routes – Like ZigBee, the 6LoWPAN protocol supports multiple network topologies. It allows for building more flexible networks and redirecting routes to reduce the load on specific network nodes used as routers.

WirelessHART is developed based on the HART protocol to enable data transmission over a radio channel instead of a cable connection [14]. The protocol uses IEEE802.15.4 as the basis for networking.

The WirelessHART energy consumption is optimized in the following ways:

– Sleep and activation mode – Wireless HART electronics have ultra-low power consumption to maximize battery life, 20 times less than a conventional 4-20 mA HART device [15]. Sleep mode allows for turning off the power when it is unnecessary. Thus, the sensor itself is turned off between two measurements. If the refresh rate is low enough, the device will go into "hibernation" as often as possible between two measurements.

– Transmitter power management – WirelessHART allows for adjusting the transmitter power depending on the communication conditions and distance to the receiver [16]. Adjusting the transmitter power to the minimum required level to ensure stable communication can reduce power consumption, mainly when devices are close to each other. By default, a transmitter with a power of 10 dBm (10 milliwatts) is used [17].

– Frequency mesh – using Direct-sequence spread-spectrum (DSSS) with frequency hopping between 15 channels in this range allows for security and reduced interference that would require retransmitting a packet to recover it [17].

– Network topology management – The WirelessHART network topology can be a star, cluster, or mesh, which provides much better scalability. It also makes it possible to control the load distribution between the base stations and limit the transmitter power, reducing end devices' overall energy consumption [18].

– Buffering and data aggregation – Data aggregation is the process of aggregating data from multiple sensors to eliminate the number of transmissions and provide fused information to the base station. Data aggregation usually involves combining data from various sensors at intermediate nodes and transmitting the aggregated data to the base station [19]. Existing data aggregation methods cannot be directly applied to the WirelessHART network due to its features, including the Multichannel Synchronized Mesh Protocol (TSMP) and superframe-based communication slot scheduling. In particular, data aggregation typically increases the end-to-end latency of packets because they may have to wait for other messages to be aggregated at intermediate nodes, potentially increasing the end-to-end latency of those packets. However, WirelessHART packets typically have strict end-to-end delay requirements, guaranteed by assigning a communication time slot in the superframe scheduling. Thus, the trade-off between energy reduction and real-time communication constraints is a significant design challenge for data aggregation in WirelessHART networks.

– Optimization of transmission routes – With a mesh network topology, you can create more flexible routes to reduce energy consumption at endpoints. It can be realized by reducing the transmitter power over shorter distances and changing the transmission in the mesh network from other nodes to the hub or less loaded nodes.

The study identified the categories by which the considered optimization methods in IoT protocols were distributed:

– Device activity time management;
– Transmission frequency management;
– Transmitter power management;
– Data packet management;
– Route management.

Using information about existing energy optimization methods, we categorized them and analyzed their impact on costs in each protocol and standard (Tables 1-3).

Table 1

Optimization by criteria for ZigBee

Category	Optimization method
Device activity time management	Sleep Mode – up to 99% [20]
Transmission frequency management	Frequency response control – up to 37% [21]
Transmitter power management	Transmitter power management – up to 70.5% [22]
Data packet management	Data aggregation and buffering – up to 49.2%
Route management	Optimization of transmission routes – up to 100%

Table 2

Optimization by criteria for 6LoWPAN

Category	Optimization method
Device activity time management	Sleep mode – up to 99% [9]
Transmission frequency management	Frequency response control – up to 5% [23]
Transmitter power management	-
Data packets management	IPv6 header compression – up to 57.1% [24]
	Fragmentation and reassembly – up to 48.3%
Route management	Optimization of transmission routes – up to 100%

Table 3

Optimization by criteria for WirelessHART

Category	Optimization method
Device activity time management	Sleep and activation mode – up to 99% [25]
Transmission frequency management	Frequency mesh – up to 3% [26]
Transmitter power management	Transmitter power management – up to 33% [25]
Data packets management	Data buffering and aggregation – up to 48.8% [25]
Route management	Optimization of transmission routes – up to 100%
	Network topology management – up to 100%

Conclusions. As a result of the research, the primary methods for optimizing energy consumption in IoT protocols were identified. Existing methods were divided into five main optimization categories, and each method's impact on energy consumption when the method is active in the protocol network was determined. The ZigBee and Wireless HART protocols have optimization methods for all the defined categories. The 6LoWPAN protocol has 4 categories of optimization methods, except for the Transmitter Power Management category.

The best energy efficiency indicators for optimization methods are "Device Activity Time Management" and "Route Management." This is because devices are turned off when data is not needed to collect and transmit. Since devices can send data from other devices to the data center, the routing setting eliminates unnecessary data transfers and leaves the device in sleep mode longer instead of waiting for data from other devices to be sent.

The worst-performing methods are those in the Frequency response control category because they are based on detecting transmissions that cause collisions. Still, devices are primarily in sleep mode, and their transmissions rarely overlap to cause collisions.

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Іванчук О.В., Козел В.М., Дроздова Є.А., Приходько О.О. ДОСЛІДЖЕННЯ МЕТОДІВ ОПТИМІЗАЦІЇ ЕНЕРГОВИТРАТ У ПРОТОКОЛАХ СТАНДАРТУ IEEE 802.15.4

У статті досліджуються існуючі методи оптимізації енергоспоживання в протоколах IEEE 802.15.4 Internet of Things. Були розглянуті такі протоколи: ZigBee, 6LoWPAN і WirelessHART. Протокол ZigBee має сплячий режим, контроль частотної характеристики, управління живленням передавача, агрегацію та буферизацію даних, а також оптимізацію маршруту передачі. 6LoWPAN використовує *сплячий режим, контроль частотної характеристики, стиснення заголовка IPv6, фрагментацію та повторне збирання, а також оптимізацію маршруту передачі. Протокол WirelessHART використовує режим сну та активації, частотну сітку, керування живленням передавача, буферизацію та агрегацію даних, оптимізацію маршруту передачі та керування топологією мережі.*

Дослідження вибрало критерії, за якими розподіляються всі методи оптимізації в протоколах IoT: управління часом активності пристрою, управління частотними характеристиками передачі, управління потужністю передавача, управління пакетами даних і управління маршрутами.

Протоколи ZigBee і Wireless HART мають методи оптимізації для всіх запропонованих категорій. Протокол 6LoWPAN має 4 категорії методів оптимізації, за винятком категорії керування живленням передавача.

Найкращі показники енергоефективності мають методи оптимізації «Керування часом активності пристрою» та «Керування маршрутом». Це тому, що пристрої вимикаються, коли дані не потрібні для збору та передачі. Оскільки пристрої можуть надсилати дані з інших пристроїв до центру обробки даних, параметр маршрутизації усуває непотрібну передачу даних і залишає пристрій у режимі сну довше замість очікування надсилання даних з інших пристроїв. Найгірше працюють методи в категорії «Керування частотою передачі», оскільки вони засновані на виявленні передач, які створюють конфлікти. Тим не менш, пристрої перебувають у режимі сну більшу частину часу, і їхні передачі рідко накладаються, тому зіткнення трапляються рідко.

Ключові слова: *Інтернет речей, стандарт IEEE 802.15.4, протоколи, енергоефективність, оптимізація, пристрої.*