p-ISSN 1607-3274 Радіоелектроніка, інформатика, управління. 2023. № 3
e-ISSN 2313-688X Radio Electronics, Computer Science, Control. 2023. № 3

UDC 621.396.946

ENERGY EFFICIENCY RESEARCH OF LPWAN TECHNOLOGIES

Lykov Y. V. – PhD, Associate Professor, Associate Professor of the Department of Computer Radio Engineering and Technical Information Protection Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine.

Gorelov D. Y. – PhD, Associate Professor, Associate Professor of the Department of Computer Radio Engineering and Technical Information Protection Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine.

Lykova A. A. – Senior Lecturer of the Department of Computer Radio Engineering and Technical Information Protection Systems, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine.

Savenko S. O. – Student of the Faculty of Information Radio Technologies and Technical Information Protection, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine.

ABSTRACT

Context. The emergence of the Internet of Things (IoT) has led to the development of various low-power wide area network (LPWAN) technologies that are designed to provide transmission of small data packets over long distances with minimal energy consumption. The two most well-known LPWAN technologies are LoRaWAN and Sigfox. This study aims to compare the energy efficiency of these two technologies to determine their suitability for use in autonomous solutions.

Objective. The objective of this study is to compare the energy efficiency of LoRaWAN and Sigfox technologies for IoT devices. The comparison will help determine which technology is better for autonomous solutions when devices need to operate for extended periods of time without frequent battery replacements.

Method. In this work, taking into account the specifications of the investigated radio technologies, mathematical modeling of the time of data transmission or reception is used depending on the payload, and information on the power supply current is taken from official datasheets for the components of the investigated devices.

Results. The results of the study show that both LoRaWAN and Sigfox are energy-saving technologies, but LoRaWAN is generally more energy-efficient than Sigfox. In addition, LoRaWAN has adaptive modes and significantly more manual settings, which in some cases further reduces the energy per bit of data compared to Sigfox.

Conclusions. LoRaWAN is the best choice for autonomous solutions where energy efficiency is crucial. This study provides valuable information for designers and developers of IoT devices, allowing them to make informed decisions when choosing LPWAN technologies for their autonomous solutions.

KEYWORDS: LoRaWAN, Sigfox, LPWAN, modem, power consumption, autonomy, IoT.

ABBREVIATIONS

IoT is Internet of Things;

LPWAN is Low Power Wide Area Network;

LoRaWAN is Long Range Wide Area Network;

PA is Power Amplifier;

SF is a spreading factor.

NOMENCLATURE

N_p is a payload size;

N_m is a number of uplink messages;

t_sleep_mcu, t_sleep_sensor, t_sleep_modem is a time to sleep of MCU, Sensor, Modem accordingly;

t_meas_sensor is a time to measurement mode of Sensor;

I_mcu_sleep, I_sensor_ sleep, I_modem_sleep is a consumption current to sleep mode of MCU, Sensor, Modem accordingly;

I_mcu_meas, I_sensor_meas, I_modem_meas is a consumption current to measurement mode of MCU, Sensor, Modem accordingly;

*I_mcu_tx, I_sensor_tx, I_modem_t*x is a consumption current to transmit mode of MCU, Sensor, Modem accordingly;

I_mcu_rx, I_sensor_rx, I_modem_rx is a consumption current to receive mode of MCU, Sensor, Modem accordingly;

V_mcu, V_sensor, V_modem is a supply voltage of MCU, Sensor, Modem accordingly;

η is a coefficient that takes into account DC/DC converter efficiency (was taken equal to 1.1)

Power_bat is a power battery (Wh);

α is a battery self-discharge;

P_sum_sleep, P_sum_meas, P_sum_tx, P_sum_rx, is a summary consumption power per day in sleep mode, in measurement mode, in transmit mode, in receive mode accordingly;

P_sum_total_per_day is a total consumption power per day;

T_symbol is a LoRa symbol duration;

BW is a Banwidth;

Number_Characters_in_Pl is a number of characters in the payload;

Payload is a payload size;

IH is a implicit mode;

DE is a low data rate optimization;

CR is a encoding speed;

T_payl_SF is a payload duration;

N_day is a number of day of autonomy.

INTRODUCTION

The IoT is a fast-paced technology. This is a set of sensors that are combined into a single network with analytical and/or control systems. Every day more and more different devices are connecting to the Internet, and this number is constantly growing. When choosing radio technology, one of the main factors that consumers

DOI 10.15588/1607-3274-2023-3-3

consider is the decrease of their maintenance costs, which is mainly determined by energy-saving parameters, or rather, the duration of the device without charging (battery replacement). New types of LPWAN can solve this problem. A technology that was created for wireless data transmission over long distances and for connecting autonomous devices to the global network. Nowadays, there are several popular technologies: LoRa, SIGFOX, NB-IoT, etc. LPWAN systems are a reliable system to transmit information over long distances (2–40km) and at the same time use a minimum of energy costs.

The development of IoT technology has led to an increase in demand for solutions with low power consumption and long-range wireless communication. Among them, LoRaWAN and Sigfox have become popular options due to their ability to support large-scale IoT device networks. However, the choice between these technologies often depends on their energy efficiency, which determines how long devices can operate without battery replacement.

The objective of this comparative study is to compare the energy efficiency of LoRaWAN and Sigfox technologies for IoT. The study aims to determine which technology is better suited for autonomous solutions where devices need to operate for long periods without frequent battery replacement. The study’s data will consist of energy consumption data for LoRaWAN and Sigfox technologies, which will be collected from existing literature, previous studies, and other official sources. In addition, the study will use available specifications and technical details of both technologies, such as transmission range, payload size, and transmission frequency.

The desired results of this comparative study are a quantitative comparison of the energy efficiency of LoRaWAN and Sigfox technologies. The comparison will be based on key energy consumption indicators, such as average energy consumption per transmitted data packet, energy consumption per transmitted data packet, and the amount of energy consumed per meter of transmitted data.

This study is limited to comparing the energy efficiency of LoRaWAN and Sigfox technologies for IoT. Other factors that may influence technology selection, such as deployment cost, infrastructure availability, and ease of integration with existing systems, are not considered in this study.

1 PROBLEM STATEMENT

Using the protocol specification of the two LPWAN technologies (LoRaWAN and Sigfox), the message transmission time is calculated with different payload sizes.

Considering the current consumption of individual nodes of a typical IoT device in different modes (in sleep mode: *I_mcu_sleep, I_sensor_sleep, I_modem_sleep;* in measurement mode: *I_mcu_meas, I_sensor_meas, I_modem_meas;* in transmit mode: *I_mcu_tx, I_sensor_tx, I_modem_tx;* in receive mode: *I_mcu_rx, I_sensor_ rx, I_modem_rx*) and battery capacity (*Power_bat*), the battery life of the End Node (*N_day*) is calculated.

The autonomy calculation was performed according to the algorithm shown in Figure 1.

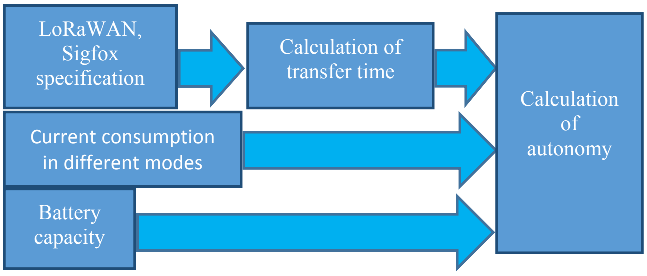

Figure 1 – Algorithm for calculating device autonomy

2 REVIEW OF THE LITERATURE

The growth of IoT technology has led to a surge of interest in low-power wide area networks (LPWANs), which provide communication between IoT devices over long distances. Two popular LPWAN technologies, LoRaWAN and Sigfox, have emerged as leading contenders due to their ability to support large-scale networks of IoT devices. However, the choice between these technologies depends on their energy efficiency, which determines the longevity of the devices and the need for frequent battery replacement.

Several previous studies have compared the energy efficiency of LoRaWAN and Sigfox technologies, but there is a need for a comprehensive comparative study that provides a quantitative comparison of the two technologies. For example, research by Atheer Al Ghamdi (2022) [1] compared the energy efficiency of Sigfox and LoRaWAN for water monitoring and leak detection systems and found that Sigfox is more energy efficient due to lower energy consumption per data packet transmitted. However, this study only considered a specific application scenario. Other scientists also dealt with the topic of energy efficiency [2–5].

An unsolved part of the overall challenge is determining which LPWAN technology is best suited for stand-alone solutions where devices need to operate for long periods of time without frequent battery replacement. This requires a comprehensive benchmarking study that takes into account various factors affecting energy consumption, such as transmission range, payload size, and transmission frequency.

The proposed benchmarking study aims to address this gap by quantitatively comparing the energy efficiency of LoRaWAN and Sigfox technologies for the IoT. The study will use the available specifications and technical details of both technologies to evaluate their energy consumption under different scenarios. The results of the study will help determine which technology is best suited for stand-alone solutions where devices need to operate for long periods of time without frequent battery replacement.

DOI 10.15588/1607-3274-2023-3-3

The creator of LoRaWAN is Semtech. Semtech Corporation is a leading supplier of high-performance analog and mixed-signal semiconductors and advanced algorithms for high-end consumer, enterprise computing, communications, and industrial end-markets. They have nearly 60 years of experience designing and manufacturing proprietary platforms differentiated by innovation, size, efficiency, performance, and reach. Original equipment manufacturers and their suppliers for automotive, broadcast equipment, data centers, passive optical networks, industrial, IoT, LCD TVs, smartphones, tablets, wearables, and wireless infrastructure applications [6] use their balanced portfolio of semiconductor products.

The LoRaWAN network consists of the following elements: end device, gateways, network server, and application server. The end device is designed for the implementation of control or measuring functions. It includes a set of necessary sensors and control elements. A gateway is a device that receives data from end devices using a radio channel and transmits them to a transit network. A network server is created to control the network: setting a schedule, adapting speed, storing, and processing received data. The application server can remotely control the operation of end devices and collect the necessary data from them [7].

LoRa has three classes of subscriber devices:

– Class A: after transmitting something on the air, the device short time waits for a response from the base station, after which it turns off the receiver until the next communication session.

– Class B: the device turns on the receiver according to a predetermined schedule. The base station knows this schedule and can transmit data to the device according to it.

– Class C: the receiver is always on; the base station can transmit data at any time [8].

Table 1 – Specifications of LORAWAN [7]

Parametr	Europe
Frequency range, MHz	863 – 870
Maximum number of channels	35
Spectrum width of radio signal UL, kHz	125/250
DL channel radio spectrum, kHz	125
Modulation	LORA, GFSK, MSK
Transmit power UL, dBm	2–14; 20 (option)
Transmit power UL, mW	1–25; 100 (option)
Transmit power DL, dBm	14
SF	7–12

The most popular LoRa Modem is the Semtech SX1276. Consider the Specifications of Semtech SX1276 [9]:

– 168dB maximum link budget;
– +20dBm – 100 mW constant RF output vs. V supply;
– +14dBm high efficiency PA;
– Programmable bit rate up to 300kbps;
– High sensitivity: down to –148dBm;
– Bullet-proof front end: IIP3 = –11dBm;
– Excellent blocking immunity;
– Low RX current of 9.9mA, 200nA register retention;
– Fully integrated synthesizer with a resolution of 61Hz;
– FSK, GFSK, MSK, GMSK, LoRa and OOK modulation;
– Built-in bit synchronizer for clock recovery;
– Preamble detection;
– 127dB Dynamic Range RSSI;
– Automatic RF Sense and CAD with ultra-fast AFC;
– Packet engine up to 256 bytes with CRC;
– Built-in temperature sensor and low battery indicator.

Physical Layer Frame: At PHY layer, a LoRa frame starts with a preamble. Apart from the synchronization function, the preamble defines the packet modulation scheme, being modulated with the same SF as the rest of the packet. Typically, the preamble duration is 12.25 Ts. The preamble is followed by a PHY Header and a Header CRC that together are 20-bits long and are encoded with the most reliable code rate of, while the rest of the frame is encoded with the code rate specified in the PHY Header. The PHY header also contains such information as payload length and whether the Payload 16-bit CRC is present in the frame. Specifically, in a LoRa network, only uplink frames contain payload CRC. PHY payload contains MAC Frame.

MAC Layer Frame: The packet processed in the MAC layer consists of a MAC Header, a MAC Payload, and a Message Integrity Code (MIC). MAC header defines protocol version and message type, i.e., whether it is a data or a management frame, whether it is transmitted in uplink or downlink, whether it shall be acknowledged. MAC Header can also notify that this is a vendor specific message. In a join procedure for end node activation, the MAC Payload can be replaced by join request or join accept messages. The entire MAC Header and MAC Payload portion is used to compute the MIC value with a network session key (Nwk_SKey). The MIC value is used to prevent the forgery of messages and authenticate the end node (Fig. 1).

Application Layer Packet: The MAC Payload handled by the Application layer consists of a Frame Header, a Frame Port, and a Frame Payload. The Frame Port value is determined depending on the application type. The Frame Payload value is encrypted with an application session key (App_SKey). This encryption is basing on the AES 128 algorithm.

Table 2 – Power consumption specification [9]

Description	Conditions	Typ	Max	Unit
Supply current in Sleep mode		0.2	1	uA
Supply current in Receive mode	LnaBoost Off, band1 LnaBoost On, band1 Bands 2&3	10.8 11.5 12.0	–	mA
Supply current in Transmit mode	RFOP = +13 dBm, on RFO_LF/HF pin	29	–	mA

DOI 10.15588/1607-3274-2023-3-3

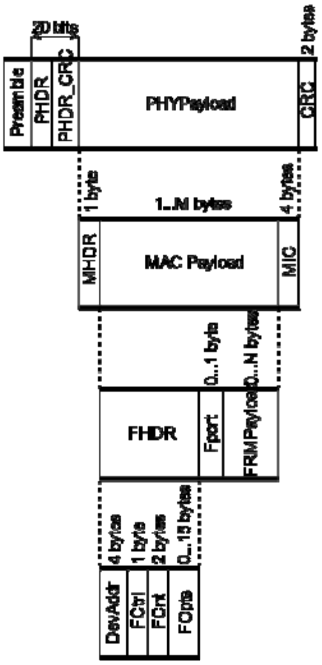

Figure 2 – LoRa Frame Format

Frame Header contains the following information:

– Device address which contains two parts. The first 8 bits identify the network, other bits are assigned dynamically during joining the network and identify the device in a network.

– Frame Control 1 byte for network control information, such as whether to use the data rate specified by the gateway for uplink transmission, whether this message acknowledges the reception of the previous message, whether the gateway has more data for the mote.

– Frame counter for sequence numbering.

Frame options for commands used to change data rate, transmission power and connection validation etc [10].

Now let's move on to Sigfox technology.

Sigfox is a French global network operator founded in 2010 that builds wireless networks to connect low-power objects such as electricity meters and smartwatches. Founders built a global network dedicated to the Internet of Things based on low power, long range and small data that offers an end-to-end connectivity service. From the inception, Sigfox powers a sustainable and connected world, pioneering the next Internet revolution [11].

The network is based on one-hop star topology and requires a mobile operator to carry the generated traffic [12]. The signal can also be used to easily cover large areas and to reach underground objects. The existing standard for Sigfox communications supports up to 140 uplink messages a day, each of which can carry a payload of 12 octets at a data rate of up to 100 bits per second.

Sigfox defines an uplink classification for each radio configuration, which applies to every device and is assessed when passing the Sigfox Ready certification. They indicate the RF radiated performance of a device, which can have a significant impact on the message success rate. They are based on EIRP (effective isotropic radiated power) intervals. Simply put, a U0 device enjoys a much better message reception than a non-U0 device. This means better user feedback and fewer support requests for your team. With a good antenna design, you can lower the device's radiated power on purpose from U0 to U1 or even U2, thus saving energy. These classes are ranked from strongest to weakest: U0, U1, U2, and U3 [13].

Each packet sent can have anywhere between 0–12 bytes of payload data, with a fixed frame of about 12 bytes that contains preamble, device id, and other metadata. In total, each packet sent has between 12–24 bytes, with some extra bits used for authentication parameters [13].

Physical layer. This synthesizes and modules signals using DBPSK in the uplink direction and GFSK in the downlink direction [14].

Table 3 – Structure of Physical Layer

Parametr	Uplink	Downlink
Payload Limit (bytes)	12	8
Throughput (bps)	100	600
Maximum Messages per Day	140	4

MAC layer This adds fields for device identification/authentication (HMAC) and error correcting code (CRC). The Sigfox MAC does not provide any signaling. This implies that devices are not synchronized with the network [14].

Frame Layer: Generates the radio frame from application data and also systematically attaches a sequence number to the frame [14] Sigfox messages can carry a payload (your own data) of 12 bytes. That's maximum, but the payload is flexible: you can send any data size between 1 and 12 bytes. You can even send a payload of 0 bytes, in case you just need a ping message [15].

One of the most popular modems for Sigfox is AX-SIP-SFEU-1-01-TX30 are ultra−low power, ultra−miniature System−in−Package solutions for a node on the Sigfox network with both up and downlink functionality. Specifications of AX-SIP-SFEU-1-01-TX30:

– Maximum output power 13 dBm;
– Power level programmable in 1 dBm steps;
– Supply range 2.1 V − 3.6 V;
– Deep Sleep mode current: 180 nA;
– Sleep mode current: 1.2 mA;
– Standby mode current: 0.55 mA;
– Continuous radio RX − mode at 869.525 MHz:
– 14 mA
– Continuous radio TX − mode at 868.130 MHz:
– 45 mA @ nominal transmitter power (13 dBm).

Receiver

– Carrier frequency of the transmitter 869.525 MHz;
– Data − rate 600 bps FSK;
– Sensitivity −125 dBm @ 600 bps, 869.525 MHz, GFSK 0 dBm maximum input power.

Transmitter

DOI 10.15588/1607-3274-2023-3-3

– Carrier frequency of the transmitter 868.13 MHz;

– Data – rate 100 bps PSK [18].

In effect, the payload bytes have to fit within a certain transmission length, predefined by the Sigfox protocol. The reason for this flexibility is to optimize transmission time and hence save battery consumption at the device level.

Downlink messages have a fixed length too: the payload must be 8 bytes long exactly. Hence, if less information bits are to be transmitted, padding is necessary [13].

Uplink frame construction shows Figure 2.

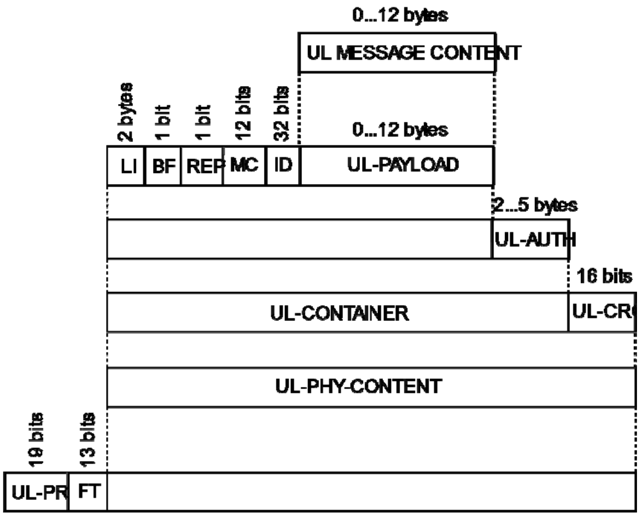

Figure 3 – Sigfox Frame Format

This section deals with formats and functions in uplink, from applicative/control level down to physical level.

Uplink message content The content of the uplink message may be applicative data or control data. The format of an applicative message content is freely defined by the application. LI values and UL-AUTH size in relation with other message parameters (Table 4).

Length Indicator (LI) It is a 2-bit field. EP shall set LI.

Repeated Flag (REP) It is a 1-bit field. EP shall set it to 0x0.

Message Counter (MC) It is a 12-bit field taking values between 0 and (MCmax-1).

Identifier (ID) It is a 32-bit field. EP shall load its EP identifier bytes in reverse order into the ID field.

Uplink Authentication (UL-AUTH) It is a variable length field.

Uplink error detection field (UL-CRC) It is a 16-bit field.

Uplink frame type (FT) It is a 13-bit field.

Uplink preamble (UL-Pr) It is a 19-bit field.

The uplink only procedure (i.e. U-procedure) is initiated by an end-point wishing to send a UL message to the SNW, with no onward downlink message. The end-point chooses the U-procedure on a per message basis.

The content of downlink message is a fixed-length field. It carries applicative data prepared by user's distant application server in response to an uplink message. Format of the DL-PAYLOAD field is user dependent [7].

Table 4 – Uplink Message Component Size

UL message content (bytes)	**UL message content**	**LI value (MSB, LSB)**	**UL-AUTH size (in bytes)**	**ULCONTAINER size (in bytes)**
empty	empty	00	2	8
0b0	empty	10	2	8
0b1	empty	11	2	8
1	message content	00	2	9
2	message content	10	4	12
3	message content	01	3	12
4	message content	00	2	12
5	message content	11	5	16
6	message content	10	4	16
7	message content	01	3	16
8	message content	00	2	16
9	message content	11	5	20
10	message content	10	4	20
11	message content	01	3	20
12	message content	00	2	20

Thus, the proposed benchmarking study builds on previous studies and the existing specification, providing a comprehensive comparison of the energy efficiency of LoRaWAN and Sigfox technologies for IoT. The research will contribute to the development of LPWAN technology by providing insight into the factors affecting power consumption.

3 MATERIALS AND METHODS

To calculate the battery life, two components are needed – the energy source and the consumer. The source was Li-ion battery (3.7V, 2000mA / h, 19% self-discharge per year). As an energy consumer, a typical solution (use case) was taken consisting of a BME280 sensor (Bosch), an MCU STM32L073, and an SX1276 modem (for LoRa) or AX-SIP-SFEU (for Sigfox).

Operation of components in different modes shown in Figure 4.

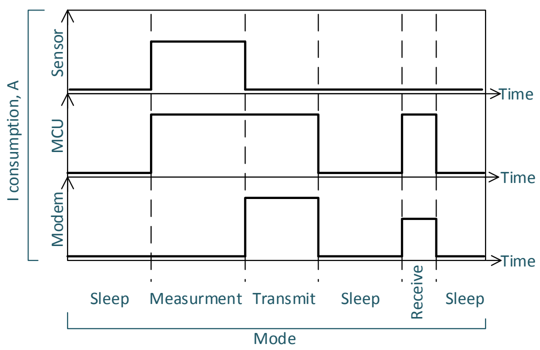

Figure 4 – Operation of devices in different modes

DOI 10.15588/1607-3274-2023-3-3

In the work, the message duration was calculated depending on the payload size. Since the maximum payload size in Sigfox is 12 bytes, then for LoRaWAN this value was taken as the maximum (although according to the protocol it can be 51–222 byte [16].

For our calculations, we will take SF 12 for LoRaWAN technology, since it is the least energy efficient but has the maximum transmission range. In order to put two different technologies (LoRaWAN and Sigfox) in the most identical conditions, as far as possible. SF is an integer, in the standard it is provided from 12 to 7. The higher the SF, the better the noise immunity of the line, but the lower the speed and the longer the transmission takes on the air.

For subsequent studies, it is necessary to calculate the duration of the preamble. First, let's find:

$$T\_symbol = \frac{2^{SF}}{BW}, \tag{1}$$

$$T\_preamble = (4.25 + N\_preamble) \times T\_symbol. \tag{2}$$

AirTime represents the duration required to transmit a message from an end device to a gateway and depends on SF, packet size, coding rate, and other parameters.

$$Number\_Characters\_in\_Pl = 8 + \max[ceil \times \left[\frac{8 \times (Payload - 4) - 4SF + 28 + 16CRC - 20(1 - IH)}{4(SF - DE)}\right] \times (CR), 0]. \tag{3}$$

Next, we calculate the duration of the payload:

$$T\_payl\_SF = Number\_Characters\_in\_Pl \times T\_symbol\_SF. \tag{4}$$

$$AirTime = T\_preamble \times T\_payl\_SF. \tag{5}$$

The calculation of consumption current was carried out for each mode individually Sleep, Measurement, Transmit (Tx), Receive (Rx).

Table 5 – Consumption Current

Mode\ Component	MCU	Sensor	Modem LoRa	Modem Sigfox
Sleep	130	0.1	0.2	0.18
Measurement	230	1.757	0.2	0.18
Transmit	230	0.1	29	45
Receive	230	0.1	10.8	14

End node battery life was calculated using the following formulas:

$$P\_sum\_sleep(N\_p, N\_m) = \frac{I\_mcu\_sleep \times t\_sleep\_mcu(N\_P,N\_m) \times V\_mcu \times \eta ... + I\_sensor\_sleep \times t\_sleep\_sensor(N\_m) \times V\_sensor \times \eta ... + I\_modem\_sleep \times t\_sleep\_modem(N\_P,N\_m) \times V\_modem}{24 \times 60 \times 60}. \tag{6}$$

$$P\_sum\_meas(N\_p,N\_m) = \frac{N\_m \times [I\_mcu\_sleep \times t\_sleep\_mcu(N\_P,N\_m) \times V\_mcu \times \eta ... + I\_sensor\_sleep \times t\_sleep\_sensor(N\_m) \times V\_sensor \times \eta. + I\_modem\_sleep \times t\_sleep\_modem(N\_P,N\_m) \times V\_modem]}{24 \times 60 \times 60}. \tag{7}$$

$$P\_sum\_tx(N\_p,N\_m) = \frac{N\_m \times [I\_mcu\_tx \times t\_tx(N\_p) \times (V\_mcu \times \eta)... + I\_sensor\_tx \times t\_sleep\_sensor(N\_m) \times (V\_sensor \times \eta) + I\_modem\_txt \times t\_tx(N\_p) \times V\_modem]}{24 \times 60 \times 60}. \tag{8}$$

$$P\_sum\_rx(N\_p,N\_m) = \frac{N\_m \times [I\_(mcu\_rx) \times t\_rx \times (V\_mcu \times \eta)... + I\_sensor\_rx \times t\_sleep\_sensor(N\_m) \times (V\_sensor \times \eta) + I\_modem\_rx \times t\_rx \times V\_modem]}{24 \times 60 \times 60}. \tag{9}$$

$$P\_sum\_total\_per\_day(N\_p,N\_m) = P\_sum\_sleep(N\_p,N\_m) + P\_sum\_meas(N\_p,N\_m) + P\_sum\_tx(N\_p,N\_m) + P\_sum\_rx(N\_p,N\_m). \tag{10}$$

$$N\_day(N\_p,N\_m) = \frac{\frac{Power\_bat}{24} \times (1 - \frac{\alpha}{100})}{P\_sum\_total\_per\_day(N\_p,N\_m)}. \tag{11}$$

4 RESULTS

Figure 6 shows the time on air which shows the number of bytes transmitted per second for each SF.

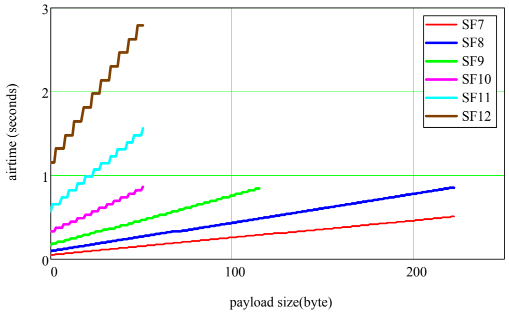

Figure 5 – Airtime for each SF

The results of calculating the power consumption for different modes are given in Table 6.

The paper shows the dependence of the number of days of autonomy on the number of messages per day (Fig. 6).

Table 6 – Power Consumption Per Day

Parametr	LoRaWAN		Sigfox	
	1 mess/day	140 mess/day	1 mess/day	140 mess/day
P_sum_sleep, W	$1.725\cdot10^{-4}$	$1.721\cdot10^{-4}$	$1.725\cdot10^{-4}$	$1.72\cdot10^{-4}$
P_sum_meas, W	$2.53\cdot10^{-11}$	$3.541\cdot10^{-9}$	$2.529\cdot10^{-11}$	$3.54\cdot10^{-9}$
P_sum_tx, W	$2.216\cdot10^{-6}$	$3.103\cdot10^{-4}$	$4.214\cdot10^{-6}$	$5.9\cdot10^{-4}$
P_sum_rx, W	0 (downlink only mode)			
$P\_sum\_total\_per\_day$, W	$1.748\cdot10^{-4}$	$4.824\cdot10^{-4}$	$1.767\cdot10^{-4}$	$7.62\cdot10^{-4}$
Self-discharge per day, W	$1.644\cdot10^{-4}$			

DOI 10.15588/1607-3274-2023-3-3

In Fig. 6 shows that for any payload from 1 bit to 12 bytes, LoRaWAN radio technology is more energy efficient for any number of messages per day. At the same time, the minimum difference of 5 days of autonomy between the considered protocols is observed with 1 single-bit message per day. And the maximum difference was 234 days for 140 12-byte messages per day.

Figure 7 displays two elements: total power in Sleep mode (taking into account battery self-discharge) and total power in transmission mode (for minimum and maximum payload). For LoRaWAN technology the number of messages per day at which these two components are equal is in the region of 85 +/–10 messages per day.

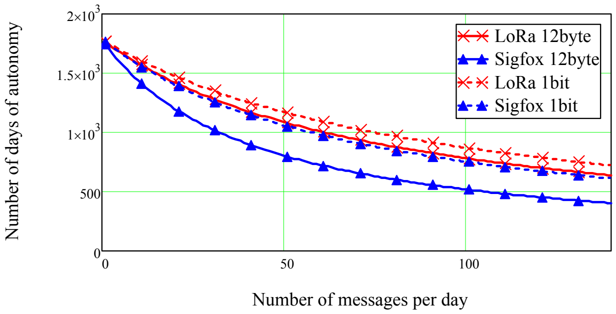

Figure 6 – Dependence of number of days of autonomy on the number of Uplink messages per day

Therefore, to increase the autonomy of the device with a small number of messages less frequently (75 messages per day), it is necessary to optimize power consumption in Sleep mode, in particular, the MCU current, which is two to three orders of magnitude higher than other nodes in this mode. Consumption in Sleep mode is practically independent of the number of messages per day (within 12 Bytes).

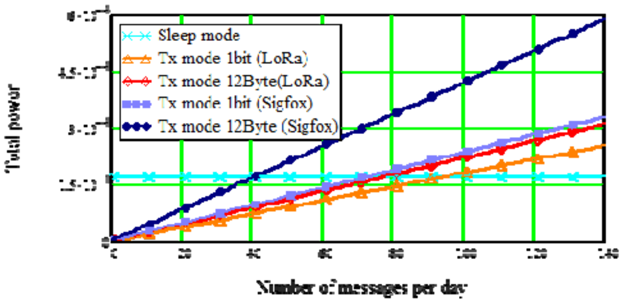

Figure 7 – Endnode power consumption in Sleep mode and in Tx mode for LoRaWAN and Sigfox

For Sigfox technology, the number of messages per day, when these two components are equal, is in the range of about 58 messages per day (+/– 16 messages).

Moreover, as can be seen from Table 6, the self-discharge of the battery is proportional to the consumption in sleep mode. So, one of the ways to increase autonomy is to use a battery with a low self-discharge and ensure the optimal operating mode (temperature, humidity).

In Figure 8 shows the results of the dependence of the number of days of autonomy on the size of the payload (from 1 bit to 12 bytes) at 1 and 140 messages per.

From Figure 8, it can be seen that for LoRaWAN, in the case of sending 1 message per day, when the payload increases, the autonomy time almost does not change (it decreases by only 4 days). When transmitting 140 messages with an increased payload, the battery life will decrease by about 85 days (with payload changes ranging from 1 bit to 12 bytes). Similarly, for Sigfox, which sends 1 message per day, the battery life decreases by 18.5 days as the payload increases. If you transmit 140 messages, it will decrease by about 209 days. In general, it can be seen that LoRaWAN maintains autonomy longer than Sigfox.

When sending 1 message, the autonomy of LoRaWAN and Sigfox is almost the same (in Sigfox, only 5 days less autonomy), but with increasing payload, the autonomy of Sigfox is significantly reduced.

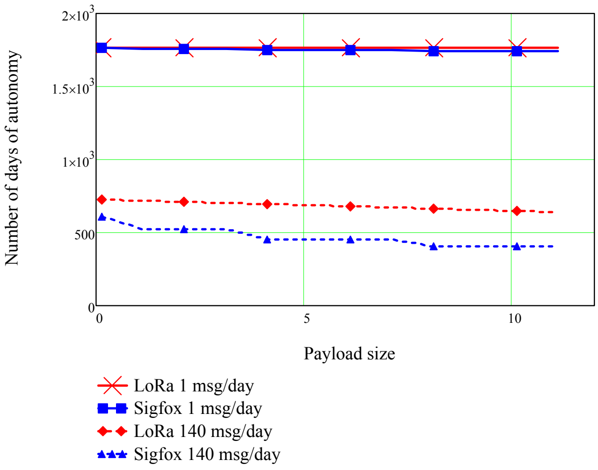

Figure 8 – Dependence of a number of days of autonomy on ther number of payloads at 1 and 140 messages per day

It should be said that previous results for Sigfox were obtained for transmission of each message without repetitions (Nrep = 1). In order to increase the reliability of message delivery from the end node to the base station, the Sigfox standard provides a mode for repeating the same message three times. In this case, the autonomy of the device will be even lower (Figure 9).

As can be seen from Figure 9, the reduction in the number of autonomous days can reach up to 60% in the case of sending 140 12-byte messages per day, and is not significant when the number of messages is less than 5 per day.

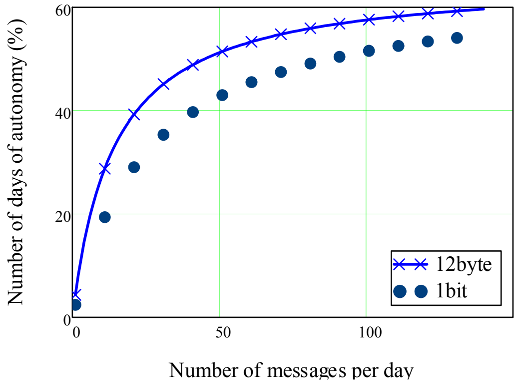

Figure 9 – Downtime reduction for Sigfox device when using Nrep = 3 instead of Nrep = 1 from number of messages per day for different payload sizes

DOI 10.15588/1607-3274-2023-3-3

5 DISCUSSION

The results of this comparative study show that LoRaWAN technology outperforms Sigfox in terms of energy efficiency for IoT. The comparison was based on the energy consumption of each technology during the transmission and reception of data packets.

However, it should be noted that the energy efficiency of LPWAN technologies can be influenced by various factors, such as the number of devices in the network, the distance between devices and gateways, the type of data transmitted, and environmental conditions. Therefore, the results of this study should be interpreted cautiously, and their generalization should be limited to specific conditions and scenarios in which the tests were conducted.

The practical significance of the obtained results is essential, especially for IoT, where there is a requirement for end devices to work for a long time without frequent battery replacement. Our results show that LoRaWAN is the best choice for such applications, as it can extend the battery life of devices and reduce network maintenance costs. In addition, the feasibility of further research into energy-efficient LPWAN technologies is justified by the growing demand for IoT solutions in various industries, including smart cities, healthcare, and logistics.

Finally, this comparative study demonstrated the energy efficiency of LoRaWAN and Sigfox technologies for IoT applications. Although LoRaWAN was found to be more energy efficient than Sigfox, the results should be interpreted in the context of specific settings and scenarios in which the tests were conducted. The study provides valuable information for researchers, practitioners, and decision-makers in choosing the most appropriate LPWAN technology for their IoT applications.

CONCLUSIONS

This benchmarking study aimed to compare the energy efficiency of LoRaWAN and Sigfox IoT technologies to determine which technology is best suited for autonomous solutions requiring long battery life. The study showed that the main sources of energy consumption were sleep mode and transmission mode. In addition, losses from self-discharge of lithium-ion batteries were equal to energy consumption in these modes. The advantage of sending one large message over multiple small messages of the same overall size has also been highlighted in terms of energy efficiency.

The results showed that LoRaWAN outperforms Sigfox in terms of energy efficiency. In particular, the size of any payload of LoRaWAN radio technology from 1 bit to 12 bytes was more energy efficient. Moreover, LoRaWAN provided additional energy optimization mechanisms such as data rate variation, including adaptive data rate, class B and C end node capability, and a much larger maximum payload size. The obtained simulation results agree with the experimental results published in [19].

It should be noted that, in addition to energy efficiency, properties such as immunity to interference, maximum network bandwidth, and price policy of communication operators are also important for consumers.

Thus, the study found that LoRaWAN is the best LPWAN technology for IoT applications requiring long battery life. The results of the study can be used in the selection of LPWAN technologies for such applications. The scientific novelty of the results lies in the comprehensive and comparative analysis of the energy efficiency of two LPWAN technologies for autonomous IoT solutions.

The practical significance of the results lies in the possibility of saving costs and increasing the productivity of IoT devices using LPWAN technologies. The results can be used to select and optimize LPWAN technologies for autonomous IoT applications.

Further research can be conducted to examine the trade-offs between energy efficiency, network bandwidth, and immunity to interference in LPWAN technologies. Additionally, future research could explore the integration of multiple LPWAN technologies to improve performance in complex IoT applications.

ACKNOWLEDGEMENTS

The authors express their gratitude to the EKTOS-Ukraine for consultations on the experience in the development of IoT devices and for the access to equipment for experimental research.

REFERENCES

1. Atheer M. Alghamdi. LoRaWAN Performance Analysis for a Water Monitoring and Leakage Detection System in a Housing Complex. Removed from: https://www.mdpi.com/1424-8220/22/19/7188
2. Husam R., Tibor C., Taoufik B. Evaluation of Energy Consumption of LPWAN Technologies. Removed from: https://www.researchgate.net/publication/350641637_Evaluation_of_Energy_Consumption_of_LPWAN_Technologies
3. Ritesh kumar S., Priyesh P. Energy Consumption Analysis of LPWAN Technologies and Lifetime Estimation for IoT Application. Removed from: https://www.researchgate.net/publication/343871606_Energy_Consumption_Analysis_of_LPWAN_Technologies_and_Lifetime_Estimation_for_IoT_Application
4. Lam-Thanh T., Abbas B. Energy Efficiency Analysis of LoRa Networks. Removed from: https://hal.science/hal-02977258/document
5. Rúni E., Energy Consumption of Low Power Wide Area Network Node Devices in the Industrial, *Scientific and Medical Band.* Removed from: https://www.diva-portal.org/smash/get/diva2:1351642/FULLTEXT01.pdf
6. Company Semtech Corporation, Removed from: https://www.semtech.com/company.
7. Обзор технологии LoRa. Removed from: https://itechinfo.ru/content/%D0%BE%D0%B1%D0%B7%D0%BE%D1%80-%D1%82%D0%B5%D1%85%D0%BD%D0%BE%D0%BB%D0%BE%D0%B3%D0%B8%D0%B8-lora.

DOI 10.15588/1607-3274-2023-3-3

8. Связь в интернете вещей: LoRa против UNB Removed from: https://habr.com/ru/company/unwds/blog/372645/.
9. Semtech. LoRa. SX1276/77/78/79. Removed from: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R0000001OKs/Bs97dmPXeatnbdoJNVMIDaKDlQz8q1N_gxDcgqi7g2o [Accessed: 2020, june 17].
10. LoRa-(Long Range) Network and Protocol Architecture with Its Frame Structure. Removed from: http://www.techplayon.com/lora-long-range-network-architecture-protocol-architecture-and-frame-formats
11. SIGFOX. Removed from: https://www.sigidwiki.com/wiki/SIGFOX
12. ОБЗОР И СРАВНИТЕЛЬНЫЙ АНАЛИЗ ТЕХНОЛОГИЙ LPWAN СЕТЕЙ. Removed from: https://www.sut.ru/doci/nauka/review/20164/33-48.pdf
13. Sigfox connected objects: Radio specifications. Removed from: https://storage.sbg.cloud.ovh.net/v1/AUTH_669d7dfced0b44518cb186841d7cbd75/prod_medias/b2be6c79-4841-4811-b9ee-61060512ecf8.pdf
14. Internet of Things for Architects. Removed from: https://cutt.ly/cuFDW2B
15. Sigfox Platform Information. Removed from: https://build.sigfox.com/payload
16. LoRa best practices Packet Optimisation Parametrs Removed from: https://lora-developers.semtech.com/library/tech-papers-and-guides/the-book/packet-size-considerations/
17. ST Microelectronics. Removed from: https://midatronics.com/development-boards/breakout-sharky-i/
18. AX-SIP-SFEU. Removed from: https://www.onsemi.com/pub/Collateral/AX-SIP-SFEU-D.PDF
19. Singh R. K., Puluckul P. P., Berkvens R., Weyn M. Energy Consumption Analysis of LPWAN Technologies and Lifetime Estimation for IoT Application Sensors 2020 Removed from: https://doi.org/10.3390/s20174794

Received 23.07.2023.
Accepted 04.09.2023.

УДК 621.396.946

ДОСЛІДЖЕННЯ ЕНЕРГОЕФЕКТИВНОСІ ТЕХНОЛОГІЙ LPWAN

Ликов Ю. В. – канд. техн. наук, доцент, доцент кафедри комп'ютерної радіотехніки та систем технічного захисту інформації Харківського національного університету радіоелектроніки, м. Харків, Україна.

Горелов Д. Ю. – канд. техн. наук, доцент, доцент кафедри комп'ютерної радіотехніки та систем технічного захисту інформації Харківського національного університету радіоелектроніки, м. Харків, Україна.

Ликова Г. О. – старший викладач кафедри комп'ютерної радіотехніки та систем технічного захисту інформації Харківського національного університету радіоелектроніки, м. Харків, Україна.

Савенко С. О. – студент факультету інформаційних радіотехнологій та технічного захисту інформації Харківського національного університету радіоелектроніки, м. Харків, Україна.

АНОТАЦІЯ

Актуальність. Поява Інтернету речей (IoT) спричинила розробку різних технологій глобальної мережі з низьким енергоспоживанням (LPWAN), які призначені для забезпечення передачі невеликих пакетів даних на великі відстані при мінімальному споживанні енергії. Двома найбільш відомими технологіями LPWAN є LoRaWAN та Sigfox. Це дослідження спрямоване на порівняння енергоефективності цих двох технологій, щоб визначити їхню придатність для використання в автономних рішеннях.

Мета. Метою цього дослідження є порівняння енергоефективності технологій LoRaWAN та Sigfox для пристроїв IoT. Порівняння допоможе визначити, яка технологія краща для автономних рішень, коли пристрої повинні працювати протягом тривалого часу без частої заміни батареї.

Метод. У роботі враховуючи специфікації досліджуємих радіотехнологій використовується математичне моделювання часу передачі або прийому даних в залежності від корисного навантаження, інформацію про струми споживання взято з офіційних специфікацій на компоненти досліджуваних пристроїв.

Результати. Результати дослідження показують, що і LoRaWAN, і Sigfox є енергозберігаючими технологіями, але LoRaWAN загалом енергоефективний, ніж Sigfox. Крім того, LoRaWAN має адаптивні режими та значно більше ручних налаштувань, що в деяких випадках ще додатково зменшить енергію на біт даних в порівняні з Sigfox.

Висновки. LoRaWAN є найкращим вибором для автономних рішень, де енергоефективність має вирішальне значення. Це дослідження дає цінну інформацію проектувальникам і розробникам пристроїв IoT, дозволяючи їм приймати обгрунтовані рішення при виборі технологій LPWAN для своїх автономних рішень.

КЛЮЧОВІ СЛОВА: LoRaWAN, Sigfox, LPWAN, модем, енергоспоживання, автономність, IoT.

ЛІТЕРАТУРА

1. Atheer M. Alghamdi. LoRaWAN Performance Analysis for a Water Monitoring and Leakage Detection System in a Housing Complex / M. Atheer. – Removed from: https://www.mdpi.com/1424-8220/22/19/7188
2. Husam R. Evaluation of Energy Consumption of LPWAN Technologies / R. Husam, C. Tibor, B. Taoufik. – Removed from: https://www.researchgate.net/publication/350641637_Evaluation_of_Energy_Consumption_of_LPWAN_Technologies
3. Ritesh kumar S. Energy Consumption Analysis of LPWAN Technologies and Lifetime Estimation for IoT Application / S. Ritesh kumar, P. Priyesh. – Removed from: https://www.researchgate.net/publication/343871606_Energy_Consumption_Analysis_of_LPWAN_Technologies_and_Lifetime_Estimation_for_IoT_Application

DOI 10.15588/1607-3274-2023-3-3

4. Lam-Thanh T., Abbas B. Energy Efficiency Analysis of LoRa Networks / T. Lam-Thanh, B. Abbas. – Removed from: https://hal.science/hal-02977258/document
5. Rúni E., Energy Consumption of Low Power Wide Area Network Node Devices in the Industrial / E. Rúni // Scientific and Medical Band. Removed from: https://www.diva-portal.org/smash/get/diva2:1351642/FULLTEXT01.pdf
6. Company Semtech Corporation, Removed from: https://www.semtech.com/company.
7. Обзор технологии LoRa. Removed from: https://itechinfo.ru/content/%D0%BE%D0%B1%D0%B7%D0%BE%D1%80-%D1%82%D0%B5%D1%85%D0%BD%D0%BE%D0%BB%D0%BE%D0%B3%D0%B8%D0%B8-lora.
8. Связь в интернете вещей: LoRa против UNB Removed from: https://habr.com/ru/company/unwds/blog/372645/.
9. Semtech. LoRa. SX1276/77/78/79. Removed from: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R0000001OKs/Bs97dmPXeatnbdoJNVMIDaKDlQz8q1N_gxDcgqi7g2o.
10. LoRa-(Long Range) Network and Protocol Architecture with Its Frame Structure. Removed from: http://www.techplayon.com/lora-long-range-network-architecture-protocol-architecture-and-frame-formats
11. SIGFOX. Removed from: https://www.sigidwiki.com/wiki/SIGFOX
12. ОБЗОР И СРАВНИТЕЛЬНЫЙ АНАЛИЗ ТЕХНОЛОГИЙ LPWAN СЕТЕЙ. Removed from: https://www.sut.ru/doci/nauka/review/20164/33-48.pdf
13. Sigfox connected objects: Radio specifications. Removed from: https://storage.sbg.cloud.ovh.net/v1/AUTH_669d7dfced0b44518cb186841d7cbd75/prod_medias/b2be6c79-4841-4811-b9ee-61060512ecf8.pdf
14. Internet of Things for Architects. Removed from: https://cutt.ly/cuFDW2B
15. Sigfox Platform Information. Removed from: https://build.sigfox.com/payload
16. LoRa best practices Packet Optimisation Parametrs Removed from: https://lora-developers.semtech.com/library/tech-papers-and-guides/the-book/packet-size-considerations/
17. ST Microelectronics. Removed from: https://midatronics.com/development-boards/breakout-sharky-i/
18. AX-SIP-SFEU. Removed from: https://www.onsemi.com/pub/Collateral/AX-SIP-SFEU-D.PDF
19. Energy Consumption Analysis of LPWAN Technologies and Lifetime Estimation for IoT Application Sensors / [R. K. Singh, P. P. Puluckul, R. Berkvens, M. Weyn], 2020 Removed from: https://doi.org/10.3390/s20174794

DOI 10.15588/1607-3274-2023-3-3