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M. K. Nurgaliyev, A. K. Saymbetov,
B. N. Zholamanov, A. T. Yeralkhanova, G. B. Zhuman

Al-Farabi Kazakh National university, Almaty, Kazakhstan.
E-mail: gulzhan.zhuman@gmail.com

PREDICTING THE LIFETIME OF LORA BASED WIRELESS SENSOR NETWORKS USING A PROBABILISTIC MODEL OF MARKOV CHAINS

Abstract. Real-time monitoring systems and sensors are not complete without wireless data transmission modules. Improving energy efficiency requires examining various system parameters that affect the power consumption of transmitting and receiving devices. The most important parameter of any autonomous wireless network is its uptime. In this work, we used LoRa wireless modules on the SX1278 chip manufactured by Semtech to determine their power consumption in various operating modes. The obtained data were used to build a consumption model of the device when connected to a receiver. Three operating modes are considered: transmit mode, receive mode and sleep mode. In an ideal communication channel, all transmitted data reaches the receiver with 100% probability. In a real situation, data reaches the receiver with a certain probability, depending on the communication channel, transmission power, distance to the addressee, and network parameters. In this work, the occurrence of an error is random. In this case, the occurrence of an error during reception entails a lack of confirmation of receipt or a request for re-sending data. Sending data again increases the power consumption of the device and, consequently, decreases the operating time of the wireless device. This paper shows the dependences of the operating time on various initial monitored parameters of the device, such as: confirmation timeout, packet length, time of one transmission cycle and the maximum number of retransmissions in one cycle. The developed model for predicting the consumption of the device can be used in the design of autonomous wireless sensor monitoring networks.

Key words: Wireless sensor networks, LoRa technology, energy efficiency, Markov chains, error probability in the communication channel.

Introduction. Wireless sensor networks (WSN) are at the heart of the ever-evolving Internet of Things (IoT) and provide a wide range of applications such as infrastructure security, environmental monitoring, event detection, etc. [1] Such applications are designed to collect information about a given phenomenon or event. These sensor nodes are typically deployed in hard and inaccessible environments. For these reasons, the sensor nodes must operate for a long period of time without human intervention [1,2].

Power consumption modeling is an important part when designing switching sensors to monitor a specific target application. Transmitting sensors must perform the following tasks for most applications [1,3]: event recognition, local processing of sensor event information, and packet transmission to the access point [3,4]. Each task consumes a certain amount of energy for a given time. Therefore, to estimate the service life of the sensor, an accurate model of the energy consumption of the sensor node is necessary [5].

Several standards have been proposed for communication in the ISM frequency bands and with low data rates, the most well-known of which are LoRa, SigFox, and Dash7 [6-9]. As Dash7 is being promoted as a medium-range technology [8], the scope for long-range networks has shifted towards LoRa and SigFox. The adjustable data rate of the LoRa standard, combined with a slightly higher level of global coverage [6,7], makes this technology very promising both for applications in the WSN and for other long-distance connections with low data rates.

To encode information, this technology uses broadband frequency-modulated pulses to achieve an expansion gain, which leads to successful packet reception at extremely low signal-to-noise ratio (SNR) levels. Due to its unique modulation, LoRa is a very versatile technology that can be adapted to different types of environments and application classes [10].

In addition, the expected performance of lora has been discussed in a decent number of other publications [9,11-14], all of them highly appreciating the potential of LoRa modulation, but some also warn of a decrease in performance as the number of end devices increases.

However, when building any sensor network, in addition to its performance, the duration of its operation plays a crucial role. To date, there are many works that describe in detail the consumption of network operation [15-17]. The articles [18-19] show the application of the method of forecasting network consumption with the probabilistic nature of sending data. This method can also be used to predict the consumption of the transmitting device with the probabilistic nature of the communication channel.

The purpose of this article is to develop a transmission device consumption model based on LoRa technology, taking into account the probabilistic nature of the communication channel. As well as the dependence of time of operation of the Autonomous transmission device from the different initial parameters such as packet length, time of acknowledgment and the maximum number of items in one cycle.

Method. Consider the operation of a transmitting device in a network consisting of one transmitter and one receiver, as shown in figure 1.

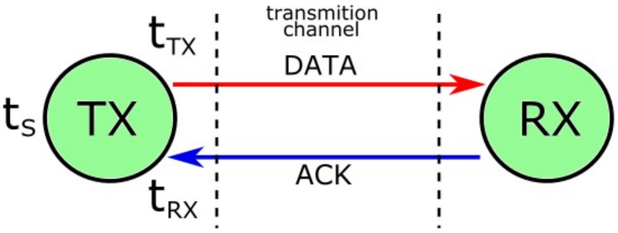

Figure 1 – Point-to-point network architecture

In general, the consumption of the transmitting device can be expressed as follows:

$$E_{Total} = E_{Sleep} + E_{Active} \quad (1)$$

$$E_{Active} = E_{Tr} + E_R \quad (2)$$

E_{Total} – total energy, E_{Sleep} – energy consumption in sleep mode, E_{Active} – consumption in active mode, E_{Tr} – consumption in data transfer mode, E_R – consumption in receive mode.

Let the time be reserved for this transmitter (time slot) T_{res}, and T_0 = 24 hours = 86400 s – the duration of one day. During the day, the transmitter manages to send M successful messages. However, there are always more attempts to send messages by the transmitter in real conditions. Let m be the number of attempts to send messages in one time slot, and N be the maximum number of possible messages sent in one time slot. Then p is the probability of sending data incorrectly, $p = \frac{m}{n}$. Figure 2 shows the detailed time distribution of the transmitter. The transmitter must wait for confirmation of receiving data from the receiver during the t_{RX} time, and only after that, the transmitter enters the sleep state until the next transmission cycle begins.

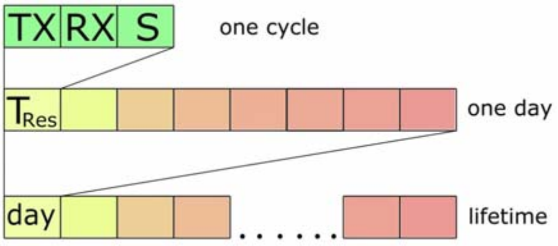

Figure 2 - Timeslots

The transmitter can be in three states during a single time slot: transmit mode, receive mode, and sleep mode. The operating time in the corresponding modes t_{TX}, t_{RX}, t_S. The probability of an error in the communication channel depends on many factors and is, generally speaking, random. Therefore, in order to analyze such processes, it is advisable to use Markov processes. Figure 3 shows the state diagram of the transmitting device. Each state corresponds to a specific consumption. The most important is the transition of the device from the RX receive state to the TX transmit state, since it is caused by a receive error in the communication channel. The probability of this transition, as we have already determined, is p. Let's construct the transition matrix (table 1) of the transmitter. By the properties of the transition matrix, the sum of the probability in the row should not be greater than 1. Using this property, we fill in the matrix cells.

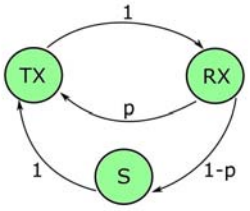

Figure 3 - State diagram of the transmitting device

Table 1 - The transition matrix of the transmitter

	TX	RX	S
TX	0	1	0
RX	p	0	1-p
S	1	0	0

The consumption of the transmitting device, depending on the error probability in the communication channel, can be determined by the following formula (1) [Wireless].

$$E_i = E_{i-1} - \left(P_{TX}t_{TX}\left[p^{(i)}(TX|RX)\right]N + P_{RX}t_{RX}\left[p^{(i)}(RX|TX)\right]N + P_S\left(T_{res} - \left[p^{(i)}(TX|RX)\right]N(t_{TX} + t_{RX})\right)\right) \tag{1}$$

E_i – remained energy in battery after i cycle, E_{i-1} – remained energy in the battery after (i-1) cycle, P_{TX} – power consumption of the device in transmission mode, P_{RX} – power consumption of the device in receive mode, P_S – power consumption of the device in sleep mode, t_{TX} – transmission time, t_{RX} – receiving time, N – maximum number of transmission per one cycle, p – transmission probability of the device, taken from Markov's transition matrix, T_{res} – time of one cycle.

To build a model of the consumption of the transmitting device under the specified conditions, we will use the LoRa-Ra01 wireless module on the Semtech SX1278 chip. These receiving and transmitting modules are characterized by a low level of consumption with a relatively large coverage area due to their unique modulation. Figure 4 shows the LoRa-01 transceiver circuit. The device is powered by two Li-ion batteries of the standard 18650 with a voltage of 3.7 V, an ATmega328 controller, and a step-down converter for voltage matching AMS1117.

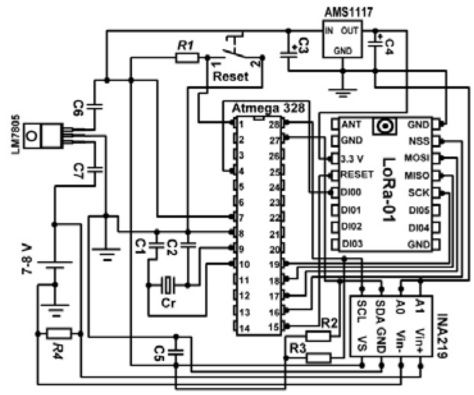

Figure 4 - Scheme of the transmitting device

Table 2 shows the consumption of the receiving and transmitting device in different operating modes.

Table 2 - Transmission device consumption in various operating modes

Operating modes of the device	Transmitter	Router
Data transmission	1085 mW/134 mA	
Data reception	250 mW/30.25 mA	
Sleep Mode	12.73 mW/13.7 mA	

Using the consumption data of the transmitting device, we will simulate the operating time of the transmitting device.

Results and discussion. Consider the operating time of the transmitting device at various initial parameters. The parameters under study will be: the initial probability of error-free data sending p, the maximum number of retransmissions in the absence of confirmation from the receiver N, the length of one data packet L, the duration of one T_{res} transmission cycle, and the waiting time for t_{RX} confirmation. Figure 5 shows the results of simulating the operation of the transmitting device for 10 different values of N with fixed values of other parameters. The abscissa axis shows the initial probability of erroneous data reception, and the ordinate axis shows the time of operation of the transmitter in months. The operating time of the device varies from 45 to 20 months with a minimum and maximum number of re-shipments, respectively. With an increase in the number of retransmissions and the probability of erroneous reception, the operating time of the transmitter also decreases, since retransmission of data is necessary. However, this change is hardly noticeable within a single curve.

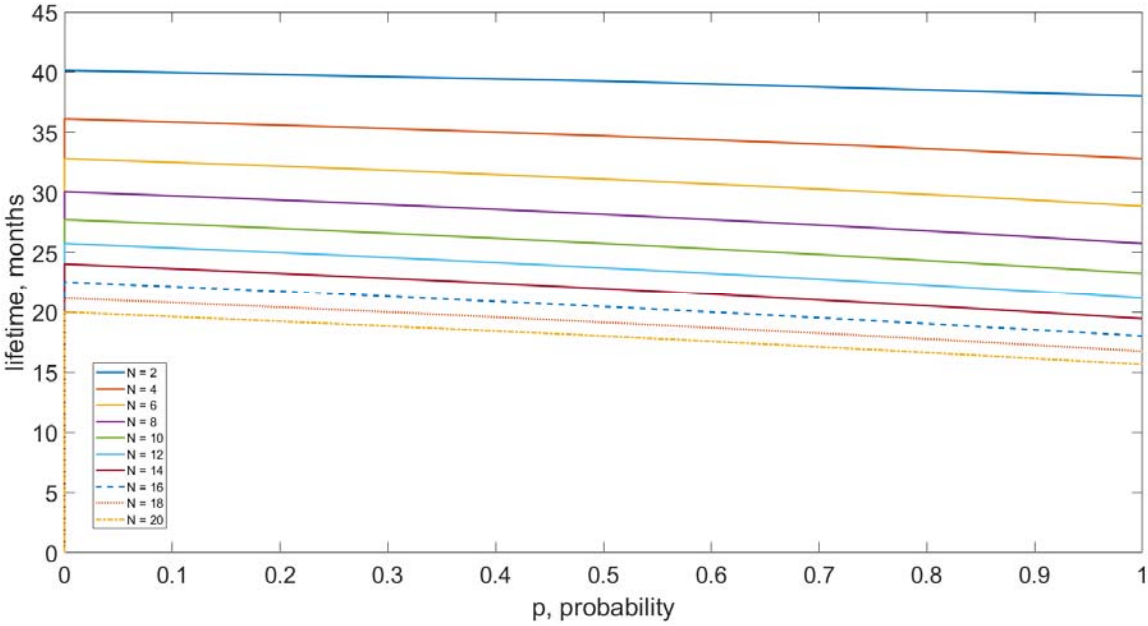

Figure 5 - Dependence of the operating time of the transmitting device on the initial probability of erroneous sending of data at different maximum numbers of retransmissions (t_{RX} = 2 s, L = 20 bytes, T_{res} = 1 hour)

Figure 6 shows graphs of the dependence of the transmitter operation time on the initial probability of an error when receiving at different packet lengths. Compared to the previous curves, the dependence of the running time on the length of the packets is more noticeable. As the packet length increases, the power consumption increases, and therefore the system operation time decreases from 30 months with 20 bytes of data to less than 20 months with 100 bytes of data being sent.

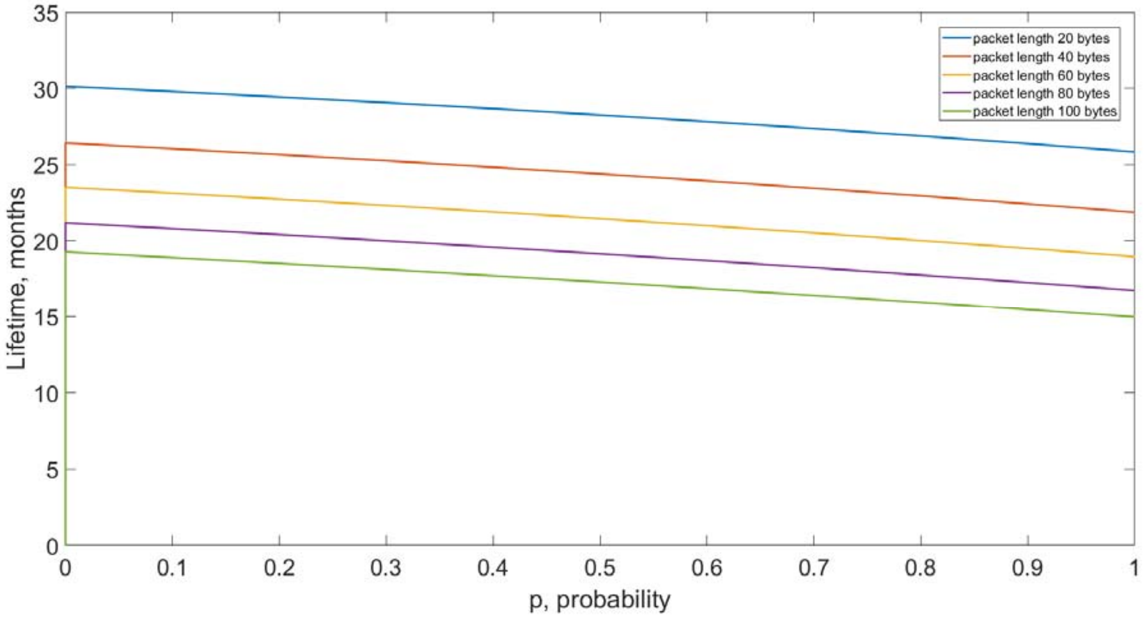

Figure 6 - Dependence of the operating time of the transmitting device on the initial probability of erroneous sending of data at different packet lengths (t_{RX} = 1 s, N = 10, T_{res} = 1 hour)

Figure 7 shows a graph of the dependence of the transmitter's operating time on the initial probability of an error in the communication channel with different confirmation waiting times.

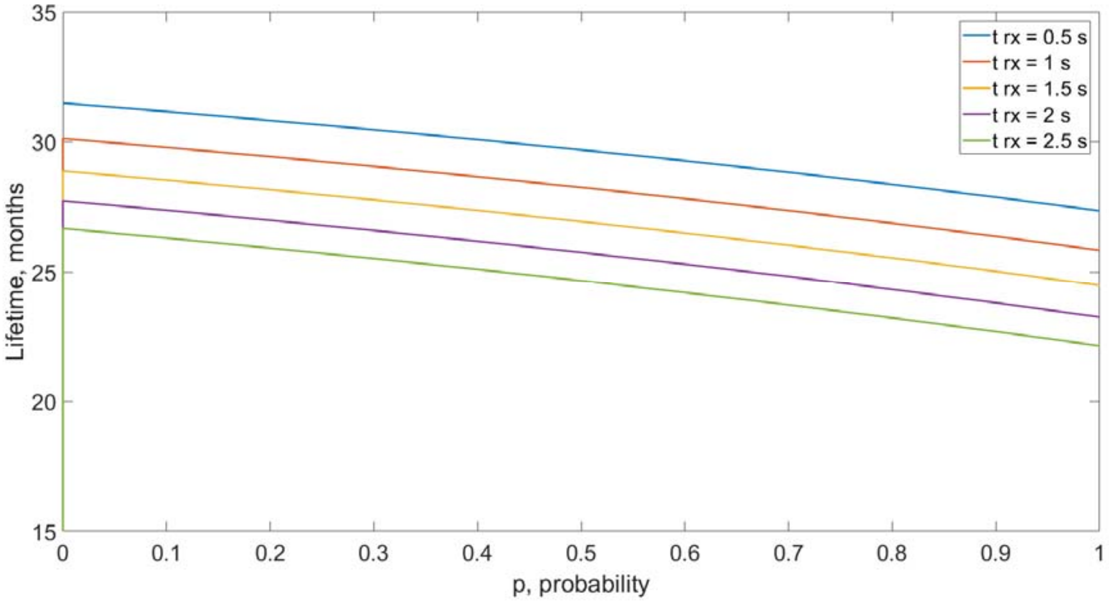

Figure 7 - Dependence of the transmission device operation time on the initial probability of erroneous data transmission with different confirmation waiting times (L = 20 bytes, N = 10, Tres = 1 hour)

As can be seen from the graphs, the operating time of the transmitters is highly dependent on the waiting time for confirmation. With the minimum waiting time, the working time reaches more than 30 months, and with the maximum waiting time-more than 25 months.

Figure 8 shows graphs of the dependence of the transmitter operation time on the initial error probability for different values of the time of one cycle.

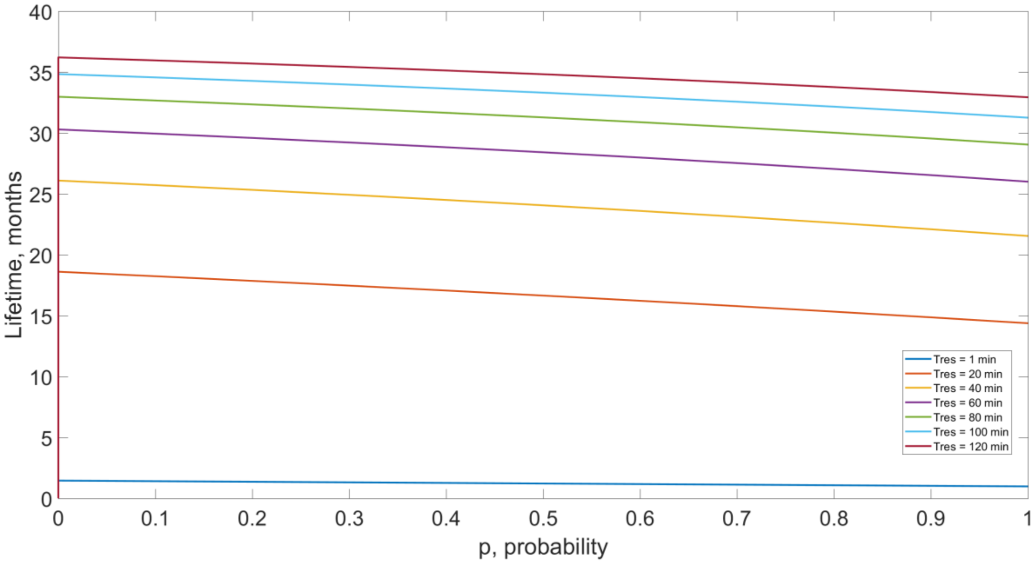

Figure 8 - Dependence of the operating time of the transmitting device on the initial probability of erroneous data sending at different durations of one cycle (L = 20 bytes, N = 10, t_{RX} = 1 s)

As can be seen from the graphs, the duration of one cycle has little effect on the operating time of the transmitter. The longer the time of a single cycle, the longer the operating time. This is due to the fact that the transmitter increases the sleep time with an increase in the time of one cycle, all other things being equal.

Conclusion. In this paper, a method for predicting the operating time of an autonomous transmitting device with a probabilistic nature of the communication channel is developed. The dependences of the operating time on various initial parameters of the transmitting device, such as: the initial probability of an error in the communication channel, the waiting time for confirmation of reception, the packet length and the duration of one cycle, are considered. An increase in any of these parameters, except for the duration of one cycle, leads to a decrease in the operating time of the autonomous transmitting device. With an increase in the initial probability of an error in the communication channel, the operating time of the transmitter, all other things being equal, also decreases. The resulting model of the transmission device consumption, taking into account errors in the communication channel, can be used to predict the operating time.

М. К. Нұрғалиев, А. К. Саймбетов,
Б. Н. Жоламанов, А. Т. Ералханова Г. Б. Жуман

[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан

МАРКОВ ТІЗБЕГІНІҢ ЫҚТИМАЛДЫ МОДЕЛІН ҚОЛДАНА ОТЫРЫП, LORA ТЕХНОЛОГИЯСЫНА НЕГІЗДЕЛГЕН СЫМСЫЗ СЕНСОРЛЫҚ ЖЕЛІЛЕРДІҢ ЖҰМЫС УАҚЫТЫН БОЛЖАУ

Аннотация. Қазіргі кездегі мониторинг жүйелері сымсыз байланыс сенсорлы жүйелерісіз өзінің толық міндетін орындай алмайды. Энергия тиімділігін арттыру үшін таратушы және қабылдаушы құрылғылардың энергия тұтынуына тәуелді болатын жүйенің әртүрлі сипаттамаларын зерттеуді талап етеді. Кез-келген автономды сымсыз желінің маңызды сипаттамасы ретінде оның жұмыс уақыты. Бұл мақалада әртүрлі жұмыс режиміндегі энергия тұтынуды анықтау үшін Semtech шығарған sx1278 микросхемасымен жасалған LoRa сымсыз модульдері қолданылды. Алынған мәліметтер қабылдағышқа қосылған кезде құрылғының энергия тұтыну моделін құру үшін пайдаланылды. Үш жұмыс режимі қарастырылған: ақпарат жіберу режимі, ақпарат қабылдау режимі және ұйқы режимі. Тамаша байланыс арнасында барлық жіберілген мәліметтер 100% ықтималдылықпен қабылдағышқа жетеді. Нақты жағдайда деректер байланыс арнасына, тарату қуатына, ақпарат қабылдаушыға дейінгі қашықтыққа және желі сипаттамаларына байланысты белгілі бір ықтималдылықпен қабылдағышқа жетеді. Бұл жұмыста қатенің пайда болуы кездейсоқ сипатқа ие. Бұл ретте ақпарат қабылдау кезінде қатенің туындауы қабылдауды растаудың болмауына немесе деректерді қайта жіберу туралы сұраныс жасауға әкеп соғады. Деректерді қайта жіберу құрылғының қуат тұтынуының артуына және сымсыз құрылғының жұмыс уақытының төмендеуіне әкеледі. Берілген мақалада құрылғының жұмыс уақытының әр түрлі бастапқы бақыланатын сипаттамаларына тәуелділігін көрсетеді, олар: растауды күту уақыты, пакеттің ұзындығы, ақпарат таратудың бір циклінің уақыты және бір циклдегі қайта ақпарат таратудың максималды саны. Жасалып шыққан, құрылғының энергия тұтынуын болжайтын модель автономды сымсыз сенсорлық бақылау желілерін жобалау кезінде пайдаланылуы мүмкін.

Түйін сөздер: Сымсыз сенсорлық желілер, LoRa технологиясы, энергия тиімділігі, Марков тізбектері, байланыс арнасындағы қателік ықтималдылығы.

М. К. Нұрғалиев, А. К. Саймбетов,
Б. Н. Жоламанов, А. Т. Ералханова Г. Б. Жуман

Казахский национальный университет им.аль-Фараби, Алматы, Казахстан

ПРОГНОЗИРОВАНИЕ ВРЕМЕНИ РАБОТЫ БЕСПРОВОДНЫХ СЕНСОРНЫХ СЕТЕЙ НА ОСНОВЕ ТЕХНОЛОГИИ LORA С ИСПОЛЬЗОВАНИЕМ ВЕРОЯТНОСТНОЙ МОДЕЛИ МАРКОВСКИХ ЦЕПЕЙ

Аннотация. Система мониторинга в реальном времени редко обходится без беспроводных сенсорных сетей. Повышение энергоэффективности требует исследования различных параметров системы, от которых зависит энергопотребление передающих и принимающих устройств. Важнейшим параметром любой автономной беспроводной сети является время ее работы. В данной работе были использованы беспроводные модули LoRa на микросхеме SX1278 производства Semtech для определения их энергопотребления в различных режимах работы. Полученные данные были использованы для построения модели потребления устройства при подключении к приемнику. Рассмотрено три режима работы: режим передачи, режим приема и режим сна. В идеальном канале связи все переданные данные со 100% вероятностью достигают приемника. В реальной ситуации данные достигают приемника с некоторой вероятностью, зависящей от канала связи, мощности передачи, расстояния до адресата и параметров сети. В данной работе возникновение ошибки носит случайный характер. При этом возникновение ошибки при приеме влечет за собой отсутствие подтверждения приема или запрос о повторной отправке данных. Повторная отправка данных приводит к повышению энергопотребления устройства и, соответственно, к снижению времени работы беспроводного устройства. В данной работе показаны зависимости времени работы от различных начальных контролируемых параметров устройства, таких как: время ожидания подтверждения, длина пакета, время одного цикла передачи и максимальное количество повторных отправлений в одном цикле. Разработанная модель прогнозирования потребления устройства может быть использована при проектировании автономных беспроводных сенсорных сетей мониторинга.

Ключевые слова: беспровлдные сенсорные сети, технология LoRa, энергоэффективность, Марковские цепи, вероятность ошибки в канале связи.

Information about authors:

Nurgaliyev M.K., Lecturer, al-Farabi Kazakh National university, Almaty, Kazakhstan; johnatlantgalt@gmail.com; https://orcid.org/0000-0002-6795-5384;

Saymbetov A.K., Associate professor, al-Farabi Kazakh National university, Almaty, Kazakhstan; ahmet.saymbetov@kaznu.kz; https://orcid.org/0000-0003-3442-8550;

Zholamanov B.N., Master student, al-Farabi Kazakh National university, Almaty, Kazakhstan; batyrbek149@gmail.com; https://orcid.org/0000-0001-8206-7425;

Yeralkhanova A.T., Master student, al-Farabi Kazakh National university, Almaty, Kazakhstan; aidana_8.99@mail.ru; https://orcid.org/0000-0001-6605-2573;

Zhuman G.B., Master student, al-Farabi Kazakh National university, Almaty, Kazakhstan; gulzhan.zhuman@gmail.com; https://orcid.org/0000-0002-9009-6995

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