Optimization Algorithms of Smart City Wireless Sensor Network Control

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Abstract

The technology of wireless sensor networks (WSN) and the main problems that accompany this technology are considered. Based on the analysis, the requirements for solving problems to optimize the work of WSN were formed. A simulation model of WSN was built, with the help of which we were able to investigate and reproduce a wireless sensor network and conduct research on the feasibility of the proposed algorithms. According to the theoretical assessment, it was determined that these algorithms will increase the lifetime of the network several times, depending on the parameters and topology of the network. A role distribution algorithm has been developed to equate network operation time to end device operation time. To increase the speed of delivery of messages from the device to the coordinator, an algorithm for allocating superframe slots is given. According to the results of experimental studies, it was found that the average delivery time of messages can be reduced up to 4 times, also, depending on the network topology and its parameters.

Keywords

Wireless sensor network, power consumption of the sensor device, role distribution algorithm, lifetime of the end device, message delivery time.

1. Introduction

"Smart home" means a set of systems that are able to interact and solve any problem without the direct participation of man. The most well-known and widespread systems are systems of automated control of light, heating or conditioning, and systems of protection, fire safety. The main component of reading information in the space of houses are various sensors, such as video surveillance, motion sensors, and everything related to it, and sensors of humidity, temperature, etc. If we take into account the climate control system, the main technology that ensures its proper operation is the technology of using wireless sensor networks (Wireless Sensor Network - WSN). They are characterized by low power consumption due to the large number of small devices that transmit a correspondingly small amount of information [1].

However, in solving many tasks, such as industrial monitoring or construction of "smart home" systems, distributed information collection systems, networks with information transmission up to 1 Mbps become relevant. This speed is sufficient for the transfer of control and information data from actuators and sensors [2]. Such networks include wireless sensor networks.

One of the main problems is to ensure high fault tolerance WSN (Wireless Sensor Network). Network failure is possible due to failures of nodes and communication channels for several reasons:

- Large number of nodes (according to probability theory).
- External adverse effects.
- Limited resource consumption of the node.

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Of the above factors that affect the stable operation of the WSN, the limited capacity of the power supply can be noted in the network and, accordingly, reduce this impact.

Thus, improving the energy efficiency of wireless sensor networks is a topical issue for many researchers, and the analysis of energy consumption and its optimization - a promising direction not only in WSN, but also in many other wireless networks.

1.1. Use of WSN in Climate Control Systems

A typical climate control system (Heating Ventilationand Air Conditioning - HVAC) consists of functionally and / or geographically distributed controllers capable of controlling various processes in a building or group of buildings both from a central host computer and via the Internet, by a unit that combines the functions of a host computer and a web server. Today's controllers have a wide range of computing capabilities and can generally control processes such as anomalous alarms, event-driven programs, time-based programs, and energy management programs. Through the communication protocol, the controllers exchange data with each other and with the host computer. Many of today's controllers can operate as stand-alone control systems in the absence of a host computer.

The basic classification of HVAC is a central system or a decentralized / local system. The type of system depends on the address of the main equipment, which should be centralized for air conditioning of the building as a whole, or decentralized for individual air conditioning of a particular area of the building [3].

Although WSNs can be easily integrated into HVAC control by replacing existing wired sensors without much refinement of the original control design, the technological requirements for WSN will differ when it is used for control compared to monitoring. In general, a higher refresh rate and greater reliability of data transmission are necessary to ensure the developed management functions and acceptable management efficiency. For example, a delay in data transmission will not cause monitoring problems, but may lead to instability of closed-loop management.

In our work we will consider the local type of climate control system and methods of data transmission management in it.

1.2. Main Technical Characteristics of WSN

One of the main problems in WSN is the creation of low-cost and tiny touch nodes. The main operation of a modern sensor network is the use of very low power methods for radio communication and data collection.

In many applications, WSN communicates with a local area network or broadband network through a gateway. The gateway acts as a bridge between the WSN and another network. This allows you to store and process data with devices that have more resources, such as a remote server. A wide area wireless network used mainly for low power devices is known as a low power wide area network (LPWAN) [4].

There are several wireless standards and solutions for connecting touch nodes. The most well-known technologies Thread and ZigBee can connect sensors operating at a frequency of 2.4 GHz with a data rate of 250 kbit / s. The IEEE 802.15.4 working group provides a standard for connecting low-power devices, and typically sensors and smart meters use one of these standards for connection [5]. These standards were designed to be simpler and cheaper than other personal networks, such as Bluetooth and Wi-Fi.

Energy is the smallest resource of WSN nodes and it determines the service life of WSN. Wireless sensor networks can be deployed in large numbers in a variety of environments, including remote ones, where adhoc communications (communications in wireless dynamic networks) are a key component. For this reason, algorithms and protocols need to address the following issues:

- Extended service life;
- Strength and resistance to failures;
- Self-configuration.

The main energy consumption and power consumption of the sensor device should be minimized, and the sensor units should be energy efficient, as their limited energy resource determines the service life [6]. To save energy, wireless sensor units usually turn off the radio when they are not in use.

It has recently been observed that by periodically switching on and off the sensing and communication capabilities of sensor nodes, we can significantly reduce the active time and thus extend the life of the network.

However, this duty cycle can lead to high network delays, route collisions, and delays in detecting neighboring devices for asynchronous sleep and scheduling [7].

These restrictions, which operate during WSN operation, require countermeasures for wireless sensor networks that should minimize traffic routing and power consumption information.

2. Problem Statement

2.1. General Requirements for Solving Problems

We need to define the basic requirements for the structure of the network with which we will work [8]:

- The amount of information transmitted by the network per unit time does not exceed the maximum limit.
- Signals are transmitted from the node to the coordinator and back.
- There is no network configuration change.

To begin with, we will assume that a significant difference in the power consumption of end devices and routers can be achieved by the maximum possible number of sets of routers that do not intersect and have some properties:

- Each of these sets is connected.
- No two sets have common points.
- Each set is connected to all network nodes.

Once a set of appropriate routers has been selected, the routing task should be solved as follows: minimize the maximum amount of data packet transmission between nodes required to deliver the message to the endpoint coordinator.

2.2. The Task of Minimizing Energy Consumption

Based on the requirements for the tasks, we can divide the devices, the power consumption of which differs, by roles—the end device, router and coordinator. The difference comes from the number of devices that are distributed across roles in the network.

Due to the fact that there are no changes in the configuration, when the network is turned on, the coordinator receives information about the number of all devices [9]. Some devices are assigned to endpoints that do not have child nodes, and the other part - routers - parent devices. At the hardware level, this means that end devices no longer have to pass on a beacon frame followed by a superframe, and this reduces their power consumption by almost half.

Next, consider a situation where the end device can “fall asleep” as soon as it receives the beacon from the parent device. However, it will not listen to the superframe if no data has been addressed to it, and it also has no data to send. The device determines the absence of sent data in the parent beacon according to the content of the received signal.

This optimization allows you to reduce energy consumption by another 3–4 times.

The faster the network, the more efficient the optimizations. In fast networks, the operating time will be determined by the charge of the routers' batteries, because they will be discharged up to 10 times faster than the end devices. To solve this problem, we build a mathematical model using a graph.

Suppose that a wireless sensor network is represented as a coherent undirected graph:

$$G = \{V, E\} \tag{1}$$

where vertices are nodes - $a_i \in V$, edges are pairs of adjacent nodes - $(a_i, a_j) \in E$, where $V = \{a_1, a_2, \dots, a_N\}$ is the set of all nodes, and node $a_0$is called the network coordinator .

Nodes are considered adjacent if there is a physical possibility of data transmission over the air in at least one direction between nodes [10]. The topology of the network will be called the subtree of the graph $G = \{V, E\}$, which has a vertex in the node a_0.

Construct all subgraphs of the graph G. This can be done, for example, as follows: assume that R_k is a set of all routers of the graph T_k,, where $k \in \overline{1, K}$.

It is possible to construct the corresponding graph in other ways, so we use the indices $k \in \overline{1, K}$.

If the roles of the nodes change dynamically, it is possible to equate the operating time of the network as a whole to the operating time of the end devices. This can be achieved by the fact that each of the nodes will play the role of the end device, and less likely to act as a router, which is discharged very quickly, as mentioned above.

The decision to change the network topology is made by the network coordinator, but the sets of simultaneously running routers change each other cyclically, for example during operation [11].

Next, we solve the problem of maximizing the operation time of the network.

Consider a subset of the sets $\{R_{k_m}\}_{m=1}^{M}$ from the set $\{R_k\}_{k=1}^{K}$. We have the number of sets M_i_with $\{R_{k_m}\}_{m=1}^{M}$, which include nodes a_i. Then the average current in the node a_i will be:

$$I_i = I_R\left(\frac{M_i}{M}\right) + I_E\left(\frac{M - M_i}{M}\right) = I_E + (I_R - I_E)\frac{M_i}{M}. \tag{2}$$

Here I_R is the average current in the node that acts as a router during the superframe, I_E is the average current in the node that acts as the end device, also during the superframe.

If at the initial time all devices are equally charged Q, then:

$$T = \min_i \frac{Q_i}{I_i} \to \max \tag{3}$$

Where Q_i is the battery charge of the device a_i. Since the batteries are charged in the same way, then it turns out that:

$$\max_i I_i = I_E + (I_R - I_E)\frac{\max_i M_i}{M} \to \min. \tag{4}$$

If the router sets $\{R_{k_m}\}_{m=1}^{M}$ are independent, then it turns out that $M_i = 1$. And then it remains that $M \to \max$.

Thus, in order to maximize the operation time of the entire network, you need to find the maximum number of independent sets of routers.

2.3. Algorithm of Role Distribution

It is necessary to solve the problem of finding the maximum number M of independent sets of routers $\{R_{k_m}\}_{m=1}^{M}$ from the graph $G = \{V, E\}$, and from the subtrees $\{T_m\}_{m=1}^{M}$.

We will use the following algorithm on the graph, which allows us to find a sufficient number of sets of routers [12]:

1. At the beginning, the vertex (coordinator) $a_0$is painted red.
2. Paint all adjacent vertices of red vertices in black.
3. In the case when none of the neighboring vertices was painted black, we complete the algorithm.
4. We will consider a set of black vertices. Select the vertex from it that has the largest number of unpainted adjacent vertices, repaint it red.
5. If all the vertices are painted, then we go further. If not - repeat the steps, starting with 2 points.
6. The tops, which are painted red, are the desired sets. Paint them green, then leave a_0 red, make the latter unpainted. Then repeat all the steps, starting from the second point.

This algorithm is "greedy" because it tries to paint the maximum number of vertices at each step.

After successful operation of the algorithm, we are able to obtain M independent sets of routers and the sets of routers R_m. Now, to get the corresponding subtree T_m, we first connect the coordinator to all its neighboring nodes, which become routers. Then we connect their neighboring vertices accordingly, and thus repeat the second point of the algorithm until all the nodes are connected.

In order for us to be able to manage the network using the algorithm described above, we need to determine exactly how the topologies will switch. Also, it is necessary to determine the order of selecting the topology from the list that was generated by the algorithm.

It should be noted that the change of topologies should not occur often, because in this case the delivery time of messages between nodes increases.

One of the optimal solutions is cyclic topology switching. One cycle will then include sequential switching of topologies, starting with $m = 1$, ending with $m = M$, where $m = m(t) -$ is the number of the topology at a given time. The lifetime of the network in each of the topologies is different, and the sum will be equal to the length of one cycle.

Each topology receives its own part of the time from the loop, and the parts are selected in relation to the decision made by the coordinator [13]. The sum of such time intervals must be equal to 1.

To optimally allocate time intervals between topologies, keep in mind that each of the sets of routers R_m has one device that limits the ability to use the entire set of routers. The limiting device has the smallest energy reserve q_m and, as a result, fails first. Also, it is possible to have an end device that is not included in any of the sets of routers R_m. When its battery life drops to zero, the network continues to function normally because it did not act as a router.

The ability to select time intervals for topologies is used in order to spend the energy of each limiting device in the set in proportion to the energy reserve.

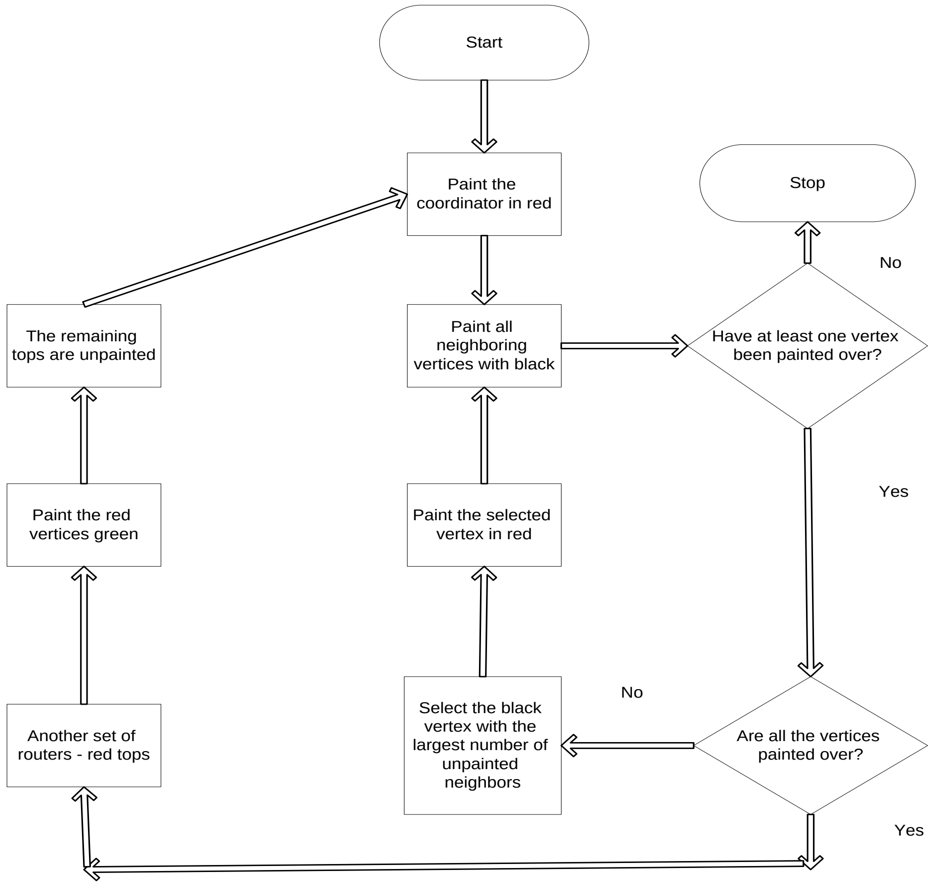

Figure 1: Scheme of the algorithm for the distribution of roles in networks

2.4. Modification of the network layer protocol

In order for us to be able to optimally change the network topologies, we need to provide access to the data of column G to the coordinator who participates in the distribution of roles. Due to the fact that the standard mode of the ZigBee protocol assumes that each device constantly sends beacons to show whether it is free for data transmission or not, it is possible to construct an adjacent graph G matrix [14]. It will be represented as a square matrix A of size n, in which the value of the element a_{ij} is equal to the number of edges from the i vertex of the graph to the j vertex.

As a result, the coordinator runs the role allocation algorithm described above, which indicates the network topology to be built.

With this algorithm, the router now has a set of nodes A to be connected to it and a set of existing dependent nodes B.

Of these two sets, the router considers 4 categories of nodes:

$\frac{A}{B}$ - nodes that need to be connected

$\frac{B}{A}$ - nodes that need to be disconnected

The rest of the nodes that should not be connected

$A \cap B$ - nodes that remain connected

To connect nodes from the $\frac{A}{B}$ set, the router adds the address of these nodes to each frame of the beacon.

Nodes from the set $A \cap B$ receive a message from the router at the same time as the subtree structure they need to build. By the way, the same message is received by nodes from the set $\frac{A}{B}$.

When a node receives a message with a new structure, the same algorithm extends beyond it, until a given topology tree is constructed [15].

2.5. The Task of Minimizing the Time of Delivery of Event Messages to the Coordinator

Now you need to calculate the delivery time of messages from any node a. By default, messages are sent from child nodes to parent nodes. Let the messaging chain be:

$$\{c_i\}_{i=1}^{d}, \text{де } c_0 = a_0, c_d = a. \tag{5}$$

Part of the delivery time is determined by the delays on the router, which are due to the superframe of the router itself and the superframe of the parent device. The set of routers $\{c_i\}_{i=1}^{d-1}$ consists of $d-2$ elements [16]. The delay on each of the routers is the number τ_{c_i} from the interval $[SD, BI - SD)$.

Then the delivery time of messages will be equal to a random variable that is evenly distributed on the interval, the mathematical expectation of which is equal to the interval between the beacons divided by two, add the sum of the delays on each of them [17]:

$$t = \frac{BI}{2} + \sum_{i=1}^{d-1} \tau_{c_i}. \tag{6}$$

Next, calculate the average for all nodes message delivery time τ_T for a random tree topology T.

$$\tau_T = \frac{BI}{2} + \frac{1}{N-1} \sum_{a \in V} w(T, a) \tau_a. \tag{7}$$

Where $w(T, a)$is the size of the subtree at the root of which is the node a.

Thus, the task of minimizing the time of delivery of event messages to the coordinator can be reduced to minimizing the value of τ_T, when the interval between the beacons remains fixed [18].

$$\sum_{a \in V} w(T, a) \tau_a \to min. \tag{8}$$

2.6. Algorithm for Allocating Superframe Slots

Let the interval between BI beacons be divided by $S = 2^{BO-SO}$ slots. Each of them will be equal to the length of the superframe. Let the number:

$$s = Sf(a) \in \overline{1, S} \tag{9}$$

- is the slot number of the superframe of node a, and it determines the time interval t between the beginning of the own beacon and the beginning of the beacon, which belongs to the coordinator [19]:

$$t = SD * s, \tag{10}$$

Equality must be met:

$$Sf(a_0) = 0. \tag{11}$$

If we have the Sf, function, we can set the delay values on the coordinator as:

$$Sf(a) - Sf(p), \text{ where } p \text{ - is the parent node to the node } a. \tag{12}$$

Based on the previous solutions, we can reduce the problem to the selection of the condition for finding Sf:

$Sf(p) \neq Sf(n)$, if p is the parent node to n

$Sf(n) \neq Sf(c)$, if n is a neighbor to c

$Sf(n) \neq Sf(h)$if h is the parent node of neighbor n

$Sf(n) \neq Sf(g)$, if g is a neighbor of the child node n,

and minimizing τ_T.

Next, we will sequentially assign the values of the function Sf to each router so that the above restrictions are met at each step [20]. From the allowable values of the function we choose a value that minimizes the value of the delay $\tau_a$on this router. We will start to bypass vertices from the coordinator in descending order of values of $w(T, a)$.

2.7. Measurement of Power Consumption of Devices

The following are calculations of the operating time of the end device and router from different types of batteries.

Table 1

Router lifetime in a stable network

BI	Average current, mA	Life time from 2*AA, years	Lifetime from a miniature galvanic cell CR2450, years
2	13.82	0.022	0.070
3	6.93	0.044	0.130
4	3.49	0.085	0.250
5	1.77	0.170	0.458
6	0.91	0.325	1.123
7	0.49	0.760	1.882
8	0.24	1.143	3.270
9	0.13	1.989	6.670

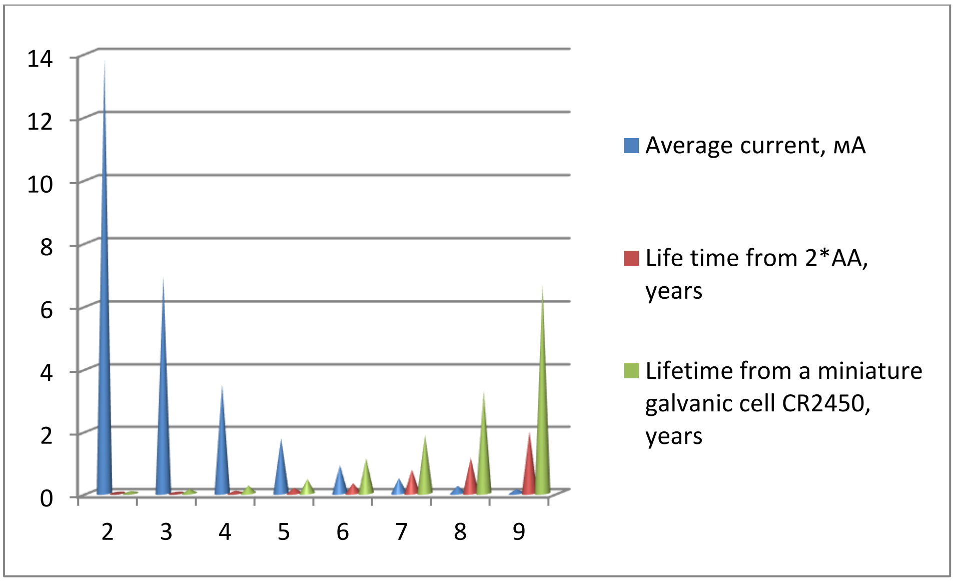

Figure 2: The dependence of the lifetime of a router with different batteries on the average current in a stable network

Table 2
Lifetime of the terminal device in a stable network

BI	Average current, mA	Life time from 2*AA, years	Lifetime from a miniature galvanic cell CR2450, years
2	7.90	0.038	0.108
3	3.96	0.074	0.213
4	2.00	0.146	0.502
5	1.02	0.290	0.912
6	0.54	0.580	1.613
7	0.27	1.030	2.970
8	0.17	1.882	5.150
9	0.11	3.124	8.272

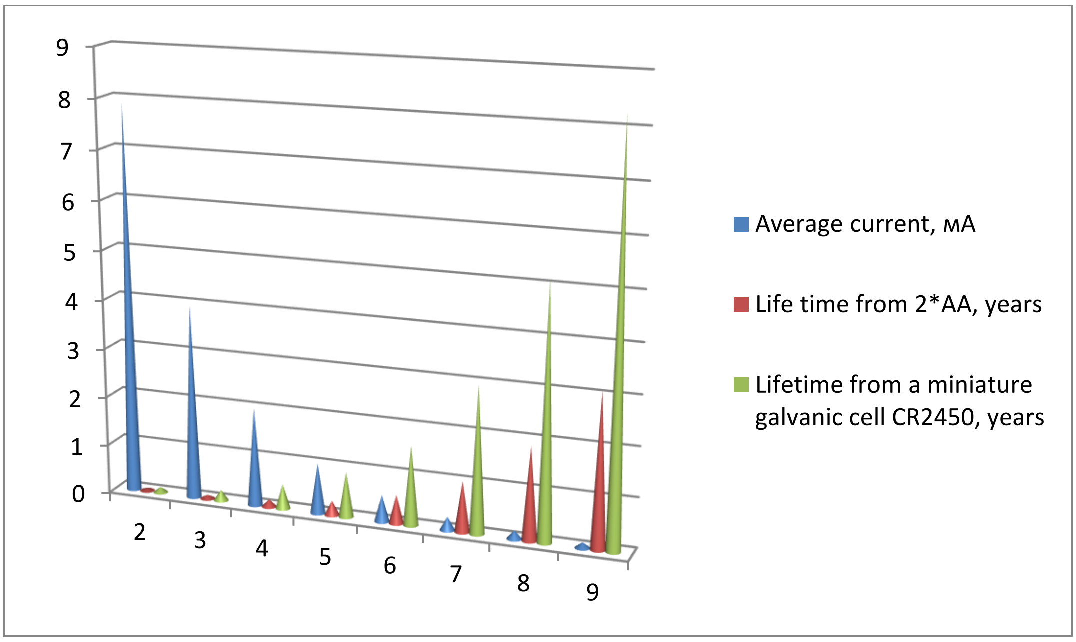

Figure 3: The dependence of the lifetime of the terminal device with different batteries on the average current in a stable network.

In Tables 1 and 2: BI - is the interval between beacons.

The table 3 shows a comparison of theoretical calculations and experimental data based on BO - beacon pointer.

Table 3
Comparison of theoretical and experimental calculations

BO	*R*(theoretical)	*R* (experimental)
2	1.995	1.740
3	1.986	1.735
4	1.972	1.726
5	1.950	1.712
6	1.894	1.687
7	1.906	1.647
8	1.764	1.571
9	1.607	1.469

In Table 3, R is ratio of average currents in the router and the end device.

Thus, the calculations confirm that the impact of traffic on the lifetime of devices in a stable network is quite small [21]. Also, the ratio of currents in different devices, distributed by roles, is about 13% less than theoretical. This confirms the feasibility of the previously constructed algorithm for the distribution of roles.

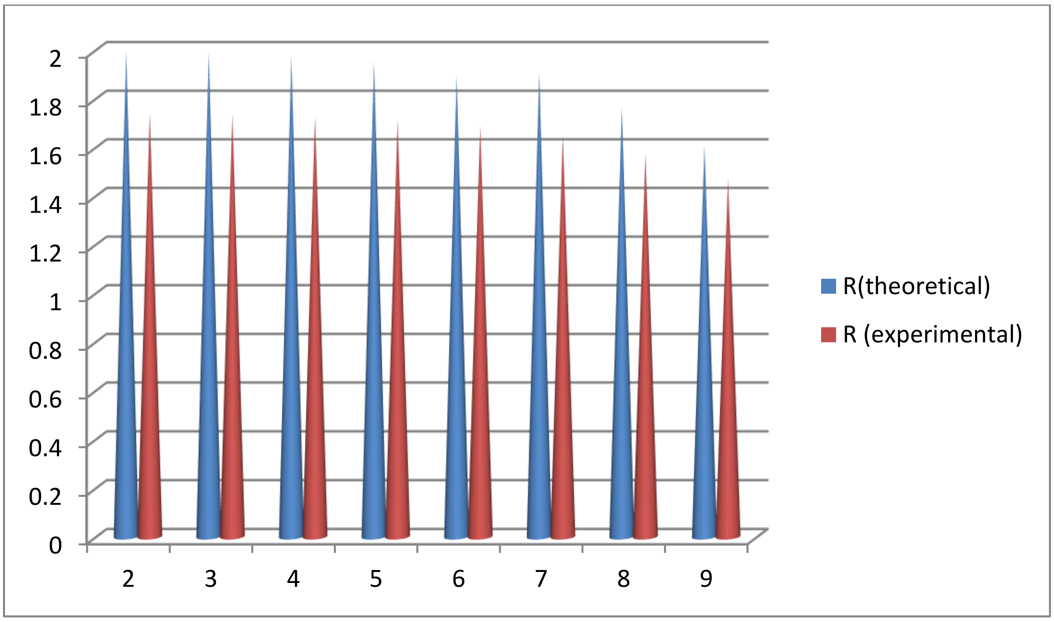

Figure 4: Dependence of the ratio of average currents in the router and the end device on the beacon indicators.

2.8. Measurement of Message Delivery Time

Several studies have been performed using the NS-2 network simulator to determine the delivery time of messages.

Different variants of schedules were used—optimal (which is determined by the algorithm of minimizing delivery time) and random [22–26].

For this study, channel-level error simulation was disabled so that data packets were delivered in one wave [27]. 4 BO parameters with optimal and random schedule were selected.

Table 4
Calculation of the distribution of messages relative to the time of their delivery

BO	**Schedule**	**Average message delivery time**	**Minimum delivery time, s**	**Maximum delivery time, s**
4	Random	0.997	0.867	1.111
	Optimal	0.306	0.170	0.451
5	Random	1.977	1.470	2.542
	Optimal	0.551	0.201	0.693

For a simple experiment, it turns out that the average message delivery time is reduced by about four times. This will depend directly on the characteristics of the network topology and its construction [28]. The data obtained experimentally for the optimal decomposition are consistent with the theoretical estimate.

3. Acknowledgements

The work is devoted to solving the problem of optimizing the wireless sensor network, which is based on the climate control system in a smart home.

The analysis of modern climate control systems and technologies used in them is carried out. Also, the technology of wireless sensor networks was considered, and, as a result, the main problems that accompany this technology. Based on the analysis, the requirements for solving problems to optimize the work of WSN were formed.

A simulation model of WSN was built, with the help of which we were able to investigate and reproduce a wireless sensor network and conduct research on the feasibility of the proposed algorithms. According to the theoretical assessment, it was determined that these algorithms will increase the lifetime of the network up to seven times, depending on the parameters and topology of the network. The theoretical estimate was overestimated by 13%.

A role distribution algorithm has been developed to equate network operation time to end device operation time. According to the results of the built optimization algorithms, the network operation time can be increased approximately 6–7 times, and the message delivery time can be reduced 2–4 times. The conducted experiments prove the optimality of the given algorithms.

4. References

[1] Xia M., Song D. (2018) Application of Wireless Sensor Network in Smart Buildings. In: Gu X., Liu G., Li B. (eds) Machine Learning and Intelligent Communications. MLICOM 2017, Pages 315-325.

[2] Lee H, Lee K. Energy Minimization for Flat Routing and Hierarchical Routing for Wireless Sensor Networks. Sensor Technologies and Applications, 2008. SENSORCOMM '08., Aug. 2008. DOI:10.1109/SENSORCOMM.2008.91

[3] Tamilselvan, K. Gandhimathi, Network coding-based energy efficient LEACH protocol for WSN, G. M. DOI https://doi.org/10.22201/icat.16656423.2019.17.1.750

[4] Wireless sensor network for HVAC applications – Access mode: https://www.researchgate.net/publication/282875781_Wireless_sensor_netwnet_for_HVAC_applications_a_review

[5] Types of HVAC Systems – Access mode: https://www.researchgate.net/publication/328948936_Types_of_HVAC_SysSyst

[6] HVAC Automation&ControlSystemsDefined[Електронний ресурс] – Access mode: https://www.arcweb.com/blog/hvac-automation-control-systems-defined

[7] Methods of the Objects Identification and Recognition Research in the Networks with the IoT Concept Support / [Olha Shevchenko, Andrii Bondarchuk, Olha Polonevych, Bohdan Zhurakovskyi, Nataliia Korshun]. Paper Proceedings of the Selected Papers on Publishing Papers with CEUR-WS co-located with Workshop on Cybersecurity Providing in Information and Telecommunication Systems (CPITS 2021), 2923, pp. 277-282. 2021.

[8] Coding for information systems security and viability / V Zhurakovskyi, B., Toliupa, S., Otrokh, S., ...Dudarieva, H., Zhurakovskyi // CEUR Workshop Proceedings, 2021, 2859. Pages 71–84.

[9] Comparative analysis of modern formats of lossy audiocompression [Electronic resource] / [B. Zhurakovskyi, N. Tsopa, Y. Batrak and other.] // CEUR Workshop Proceedings. – 2020. – Access mode: http://ceur-ws.org/Vol-2654/paper25.pdf.

[10] Al-Karaki J.N., Kamal A.E. Routing techniques in wireless sensor networks: a survey. IEEE Wireless Communications, vol. 11, no. 6, pp. 6-28, 2004.

[11] Koubda A., Alves M., Tovar E. A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks. Proceedings of the 6th IEEE International Workshop on Factory Communication Systems (WFCS 2006), Torino (Italy), 2006.

[12] Features of processing signals from stationary radiation sources in multi-position radio monitoring systems. / [Druzhynin, V., Toliupa, S., Pliushch, O., Stepanov, M., Zhurakovskyi, B.] // CEUR Workshop Proceedings, 2746, pp. 46-65 . – 2020.

[13] Increasing the efficiency of information transmission in communication channels / [B. Zhurakovskyi, Y. Boiko, V. Druzhynin et al.]. // Indonesian Journal of Electrical Engineering and Computer Science. – 2020. – Vol 19, №3 - C. 1306–1315. DOI: http://doi.org/10.11591/ijeecs.v19.i3.pp1306-1315.

[14] Zhurakovskyi B. Algorithm for detecting and troubleshooting multiservice networks. / B. Zhurakovskyi, M.S. Moshenchenko, V.B. Zhurakovskyi. // Aktualnye nauchnye issledovania v sovremennom mire. – 2020. – №5. – Pages 94–101. (in Ukrainian).

[15] Akyildiz, I.F., et al., Wireless sensor networks: a survey. Computer networks, Volume 38, Issue 4, 15 March 2002, Pages 393-422. https://doi.org/10.1016/S1389-1286(01)00302-4

[16] Zhurakovskiy B. Assessment Technique and Selection of Interconnecting Line of Information Networks [Electronic resource] / B. Zhurakovskiy, N. Tsopa // 3rd International Conference on Advanced Information and Communications Technologies (AICT). – 2019. – Access mode: DOI: 10.1109/AIACT.2019.8847726. Proceedings (2019). Pages 71-75.

[17] IEEE TG 15.4. Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LRWPANs), IEEE standard for Information Technology.

[18] Zhurakovskyi B. Processing of information in sensory framing / B.Yu. Zhurakovskyi, I. R. Parkhomey, V. A. Druzhinin // Adaptive systems and automatic control. - 2018. - No. 1. - P. 42-57. - Access mode: http://nbuv.gov.ua/UJRN/asau_2018_1_7

[19] Callaway E., Gorday P., Hester L., Gutierrez J., Naeve M., Heile B., and Bahl V. Home networking with IEEE 802.15.4: a developing standard for low-rate wireless personal area networks. IEEE Communications Magazine, vol. 40, no. 8, pp. 70-77, Aug. 2002.

[20] Hempstead, Michael J. Lyons, David Brooks, and Gu-Yeon Wei, Survey of Hardware Systems for Wireless Sensor Networks, Mark, Journal of Low Power Electronics Vol.4, 2008

[21] Wireless Sensor Networks Security: State of the Art – Access mode: https://arxiv.org/ftp/arxiv/papers/1808/1808.05272.pdf

[22] TajDini, M., et al., Wireless Sensors for Brain Activity—A Survey. In Electronics, Vol. 9, Issue 12, 2092. MDPI AG., 2020. https://doi.org/10.3390/electronics9122092

[23] Bogachuk, I., Sokolov, V., Buriachok, V., Monitoring subsystem for wireless systems based on miniature spectrum analyzers, in: International Scientific-Practical Conference Problems of Infocommunications. Science and Technology, 2018. https://doi.org/10.1109/infocommst.2018.8632151.

[24] Kipchuk, F., et al. Investigation of Availability of Wireless Access Points based on Embedded Systems. 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PICS&T), 2019. https://doi.org/10.1109/picst47496.2019.9061551

[25] Buriachok, V., Sokolov, V., Skladannyi, P., Security rating metrics for distributed wireless systems, in: Workshop of the 8th International Conference on "Mathematics. Information Technologies. Education": Modern Machine Learning Technologies and Data Science (MoMLeT and DS), vol. 2386, 222–233, 2019.

[26] Bernard P. Zeigler; Herbert Praehofer; Tag Gon Kim (2000). Theory of modeling and simulation: Integrating discrete event and continuous complex dynamic systems – second edition. Academic Press.

[27] Mathematical support for automated design systems for passive optical networks based on the β-parametric approximation formula / [Nedashkivskiy O, Havrylko Y, Zhurakovskyi B et al.] // International Journal of Advanced Trends in Computer Science and Engineering (2020) 9(5) Pages 8207-8212. DOI: 10.30534/ijatcse/2020/186952020.

[28] Limitations of efficiency of wireless systems of telecommunications 5G and methods of their compensation. / [Kremenetskaya, Y., Makarenko, A., Markov, S., Koval, V.] // 2019 IEEE International Scientific-Practical Conference: Problems of Infocommunications Science and Technology, PIC S and T, 2019 - Proceedings, 2019. Pages 493–496, 9061493.