Energy Consumption of Sensor Devices in Three-dimensional Space of Agricultural Land

Tatyana Astakhova[1[0000−0002−7032−0697]], Mikhail Kolbanev[2[0000−0003−4825−6972]], and Anna Romanova[1,2[0000−0002−8940−8111]]

Nizhny Novgorod State University of Engineering and Economics, Russia
ctn_af@mail.ru, anya-romanova-07@yandex.ru
St. Petersburg State Electrotechnical University "LETI", Russia
mokolbanev@mail.ru

Abstract. We consider a wireless sensor network (BSS), which provides data exchange between sensor devices (SU) with autonomous power, randomly distributed in three-dimensional space of agricultural land. It is shown that the lack of centralized power supply for the sensor device poses specific challenges for developers of wireless sensor networks related to the need to increase the operating time of sensor devices without replacing or recharging the battery and to reduce the power consumption of each sensor device and (or) all network devices in total. In this regard, there is an urgent task of assessing the probability-energy characteristics of wireless sensor networks and each individual device.
An analysis is made of the features of the energy consumption process of wireless sensor networks in agricultural applications, indicators are selected to evaluate the energy consumption characteristics, and models and methods for evaluating the characteristics of sensor devices are proposed that take into account the spatial, temporal and energy characteristics of the sensor network, such as the geometric size and density of the sensor field , frequency range of interaction, strategy for selecting a relaying touch device when forming Vania message transmission route to the base station.Are given are given of the dependence of the probabilistic-energetic characteristics of sensor devices on the listed parameters. The presented models and methods can be used to solve a wide range of problems arising in the development of protocols for the operation of wireless sensor networks.

Keywords: sensory device · Internet of things · probabilistic energy characteristics · agricultural land · wireless sensor network · Poisson field · spatial characteristics · three-dimensional space

1 Introduction

Among the information systems of the third platform of information, providing a transition to a digital economy, is the Internet of things.By definition, [1, 2], is "a global infrastructure of the information society that provides advanced information services by organizing communication between things (physical or virtual) based on existing and developing compatible information and communication technologies".

One of the most important subject areas of the Internet of things is agriculture, the digital transformation of which involves the creation of platform solutions aimed at:

- intellectual management of agricultural land;
- work with data on the state of soils, plants and ecosystems;
- collection of data on garden agribusinesses;
- closed farm management;
- use in livestock complexes, etc.

The implementation of any of these digital platforms involves the use of a large number of sensor devices that must be distributed in the space of agricultural land, measure the physical characteristics of agricultural environments, form sensor networks and transmit the collected information in real time to data processing and storage centers for complex analysis and adoption management decisions.

The systemic properties of the Internet of things depend mainly on the properties of wireless sensor networks, which, using identification technologies, sensors, wireless communications and autonomous power supply, provide data exchange between a large number of sensor devices, distributed and possibly moving in some space. Each of the sensor devices provides a measurement of the physical parameters of the adjacent part of the general environment and has an information image located in cloud structures. Thus, collectively, sensor devices allow the formation of dynamically changing big data on the state of various macro objects, an example of which with regard to agriculture can be a field, greenhouse, farm or garden.

The recommendations [1, 2] introduce the term "smart thing" (things), which can be regarded as a synonym for the term "sensory device". Both the sensor device and the smart thing are physical objects that have an identifier connected to the info-communication network and have sensors for measuring the parameters of the surrounding space. From the point of view of network technologies, touch devices are self-powered network terminals and their touch capabilities recede into the background, so the smart thing "turns" into a device. Depending on the context, we will use both terms.

The lack of centralized power supply to the terminals poses specific challenges for developers of wireless sensor networks related to the need to increase the operating time of sensor devices without replacing or recharging the battery, and for this to reduce the power consumption of each sensor device and (or) all network devices in total.

The energy consumer in the sensor device is a group of sensors, a data processing subsystem, a communication subsystem and a radio transmitter [3], but the main consumer is a radio transmitter, which needs about a million times more energy to transmit one bit of data than when processing this bit with a micro controller. This circumstance makes the energy consumption process random, depending on the changing size of the space covered by the wireless sensor network, and on the relative position of interacting devices, and on the intensity of information exchange, and on the volume of served traffic, and on many other random factors. In addition, communication with remote devices may be lost at a random time due to insufficient battery at the device - the data source.

In this regard, there is an urgent task of assessing the probability-energy characteristics of wireless sensor networks and each individual device. Such assessments are necessary for making decisions in the process of network self-organization in accordance with the changing external and internal functioning conditions.

The purpose of this study is to develop models for assessing the probabilistic and energetic characteristics of sensor devices in the three-dimensional space of agricultural land, which take into account the complex influence on the energy consumption of spatial and probabilistic-temporal characteristics of wireless sensor networks, as well as algorithms for selecting relay sensors in the formation of message transmission routes to the base station.

To achieve this goal, the following tasks were solved:

- analysis of the features of the energy consumption process of wireless sensor networks in agricultural applications;
- selection of indicators for assessing the energy consumption characteristics of sensor devices in three-dimensional space and the development of models for evaluating these indicators;
- numerical analysis of energy consumption of wireless sensor networks.

2 Methods

An integral component of the IT infrastructure of the digital economy are wired and wireless communication networks [4]. Given the scale of the IT infrastructure, all network characteristics should be divided into three large groups: spatial, temporal, and energy. Spatial characteristics define a geometric measure that determines the coordinates and relative position in space of users, data, and elements of the topological network infrastructure. They are measured in units of length and distance, determine the coverage area, the scale of the network, describe the topological properties of the structures that make up the network.

Time characteristics set a measure for comparing the sequence and frequency (speed) of events that change the state of data in the process of information exchange between network elements. These include the intensities of the occurrence of certain events, the load serviced by certain network elements, the times of data distribution through communication channels, waiting times for the start of service, and other random variables.

Energy characteristics, in turn, set a measure for assessing the efforts that must be made to ensure the movement of information objects, such as messages, signal bits or data blocks, in space and time in the process of information exchange. An example of such characteristics are:

- the amount of energy consumed per one data block or unit of information services;
- the amount of carbon emissions in terms of one server or group of users;
- the ratio of energy consumption of information equipment and engineering systems that support its work;
- power consumption per 1 square. m. area of technical premises;
- transaction value in kilowatt hours or carbon emissions, etc.

Wired and wireless networks differ from each other in terms of the need for spatial, temporal and energy resources and, accordingly, the target indicators for their use. The development goal of wired communication networks are:

- in the field of spatial characteristics - an increase in the number of users by increasing the coverage area of hierarchically organized and stationary stations and network nodes;
- in the field of temporal characteristics - an increase in network bandwidth and processing speeds of service data (metadata) to reduce delays and blockages in the transmission of messages;
- in the field of energy characteristics - ensuring uninterrupted power supply due to redundancy of power supply systems and energy storage directly in stations and nodes of communication networks.

Unlike wired networks, the need for the resources of the Internet of things is significantly affected by the specific properties of wireless sensor networks and their terminals, which include:

- a wide range of geometric sizes from fractions of meters to kilometers, and the ability to scale;
- autonomy of each sensor device, which has its own power and operates according to its own algorithm;
- a wide variety of sensors that carry out complex measurements of the most diverse parameters of space;
- the ability to self-organize in case of a random change in the number and location of interacting sensors due to their failures, transition to sleep mode, mobility, etc.;
- use of radio signal transmission technologies.
- a wide range of data transfer rates and acceptable response times to events, etc

These features determine the composition and target values of the characteristics of wireless networks. The main spatial characteristic is the size of the sensor field. In contrast to the coverage area of infrastructure networks, the sensor field can:

- accommodate thousands of devices, including nanodevices requiring integrated management;

– be both two-dimensional (agricultural field), and three-dimensional (either a farm or a greenhouse).change linear dimensions, which depend on random movements of devices.

All other spatial characteristics depend on the area or volume of the sensor field and the number of connected devices. The mathematical model of the sensor field is a random field of points - a collection of points that are randomly distributed in space. Field density is the average number of points per unit area (volume). Dense and superdense sensory fields are distinguished. A uniform field is a field whose density is a constant.

In many applications, the sensor field can be described by the Poisson field of points, which has the following properties:

– the probability of the appearance of one or another number of points in any area of the plane (space) does not depend on how many points fell in any areas that do not intersect with this one;
– the probability of falling into the elementary region of two or more points is negligible compared to the probability of a single point.

The number of points of the Poisson field falling in any region of space having volume S is distributed according to Poisson's law:

$$P_m = \frac{a^m}{m!}\, e^{-a}, a = S \cdot \lambda \tag{1}$$

where a–the expectation of the number of points in the selected area $S, \lambda,$– distribution density of sensor devices in volume.

The distance between the nearest points of the Poisson field is a random variable r¿ 0, which in volume is determined by the following distribution functions $F_1(r)$ and probability density $f_1(r)$ [5]:

$$F_1(r) = 1 - \mathrm{e}^{-\frac{4}{3}\,\pi\, r^3 \lambda} \tag{2}$$

$$f_1(r) = 4\,\pi\lambda r^2 e^{-\frac{4}{3}\,\pi r^3 \lambda} \tag{3}$$

where r is the distance between the antennas of the objects of wireless sensor networks in meters.

Then the average distance from an arbitrarily selected touch device to the nearest touch device is calculated by the formula:

$$\bar{r}_1 = \frac{\sqrt[3]{\pi^2}\,\sqrt[6]{3^5}\,\sqrt[3]{2}}{9\,\sqrt[3]{\lambda}\varGamma\left(\frac{2}{3}\right)} \tag{4}$$

where $\varGamma()$ is the gamma function.

For the distribution function $F_n(r)$ and density $f_n(r)$ of the probability of the distance to the n-th remoteness of a point of a Poisson field on the plane, the formulas are valid:

$$F_n(r) = -\frac{\varGamma\left(n, \frac{4}{3}\pi\lambda r^3\right) - \varGamma\left(n\right)}{\varGamma\left(n\right)} \tag{5}$$

$$f_1(r) = \frac{3^{1-n} \mathrm{e}^{-\frac{4}{3}\pi r^3 \lambda} r^{3n-1} 4^n \pi^n \lambda^n}{\Gamma(n)} \tag{6}$$

The average distance to the n-th smart thing is calculated by the formula:

$$\bar{r}_n = \frac{\sqrt[3]{3^3}\,\sqrt[3]{2}\,\Gamma\left(\frac{1}{3}+n\right)}{2\sqrt[3]{\pi^3}\sqrt{\lambda}\,\Gamma(n)} \tag{7}$$

The requirements for the probabilistic-temporal characteristics of wireless networks also differ significantly from the requirements for wired networks. One of the main differences is the time requirements for data delivery by wireless sensor networks, which can vary widely. If in wired networks of the NGN standard a single maximum allowable delay of 100 ms is established for data transfer between any network elements, then the requirements for delays on the Internet of things completely depend on the type of physical processes taking place in the subject area of the wireless network and recorded by sensors of sensor devices.

For example, in agricultural applications, sensors measuring soil temperature can be polled once every few days, and the permissible time for their reaction to the polling signal can be measured in seconds. Very different latency requirements are imposed on networks that measure animal health. Only a reduction in delay of up to 10 ms allows veterinary applications to change the traditional animal treatment model. At the same time, devices worn by animals can both monitor the course of treatment, evaluate the effect of medications, record changes in physical indicators, the course of rehabilitation, and affect the state of the animal with the help of special actuators.

For NGN networks, in which the timely delivery of a data packet from a source to a receiver is the main design task, a large number of models have been developed for assessing the probability-time characteristics and optimization according to relevant criteria [6]. Most of these models can also be used for wireless sensor networks.

The fundamental difference between sensor devices and wired network terminals is associated with autonomous power supply. For this reason, the lifetime of sensor networks depends on the duration of the energy sources of each device, and energy saving is an important priority for developers of wireless networks [7]. To save battery power, use hardware-software and system methods. The first are related to device manufacturing technologies. It is necessary to focus on the modern process technology and reliability [8] when choosing chips and other components, strive to reduce the supply voltage, apply effective circuit solutions, use system software that matches the characteristics of touch devices, develop effective data preprocessing algorithms, and strive to increase the sleep period devices, etc

Analysis of a typical energy profile of sensor devices, taking into account the phases of data collection, processing, reception and transmission, and sleep, shows the following [9]:

- the main consumer of energy is the transceiver;

- energy consumption at the stages of data processing is much less than when they are transmitted over the air;
- we must strive for preprocessing, data compression to reduce the amount of transmitted bits;
- the main part of life, a thing must sleep.

Systemic methods of energy saving are focused on the rational construction of the physical environment and algorithms for the interaction of devices with each other and other network elements. The basis of decisions at this stage of development should be based on the following premises [10]:

- the network topology defines the rules for the physical interaction of network elements with each other and, therefore, affects the levels of signals emitted by the elements;
- protocols of the physical, data link and network layers should be built on the basis of increasing the lifetime of the network as a whole (for example, the EBMR (Energy-Balancing Multipath Routing) routing protocol is based on energy balancing of the route, clustering reduces the distance between interacting smart things);
- additional (service) traffic significantly increases the energy consumption of devices (for example, LTE service traffic is many times greater than voice traffic per day);
- noise-resistant coding and acknowledgment are energy-consuming procedures. Perhaps the influence of errors should be reduced by increasing the level of emitted signals or correcting errors by upper-level protocols;
- data compression is one of the effective mechanisms for reducing energy consumption by smart things, due to the reduction in the number of emitted signs.

The energy consumed by sensor devices substantially depends on both spatial and temporal characteristics of sensor networks.

Spatial characteristics affect the power consumption of sensor devices, since increasing the distance between interacting devices requires increasing the signal power at the transmitting antenna in accordance with the Friis formula [11, 12]:

$$E_{per} = \frac{\pi^2 r^2 E_{pr} \varphi^2}{C_{per} C_{pr}} \quad (8)$$

Where E_{per}, E_{pr} is the signal power at the antennas of the transmitter and receiver, respectively [W], C_{per}, C_{pr} is the gain of transmit and receive antennas, v_c is the speed of light, f is the frequency transmission range $\varphi = \frac{f}{v_c}$ is the wavelength.

The Friis formula allows one to obtain estimates for the admissible distance between interacting devices:

$$r = \frac{\varphi}{4\pi\sqrt{E_{pr}}} \sqrt{C_{per} C_{pr} E_{per}} \quad (9)$$

You can use this formula if you know:

- the smallest acceptable signal level at the receiving antenna, depending on the sensitivity of the radio and the level of interference;
- signal level at the transmitting antenna, which determines the energy consumption of sensor devices;
- the conditions for the propagation of radio signals in the amount of agricultural land, usually characterized by the absence of dense buildings.

Thus, the power spent on signal transmission directly depends on the size of the sensor field and on the density of the devices placed in it.

Temporal characteristics affect energy consumption through the intensity of occurrence and duration t periods of activity of devices during which certain radio signals are emitted.

The energy e spent on the transmission of one data block by a touch device can be estimated by the formula:

$$e = E_{per} \cdot t \tag{10}$$

in which the spatial characteristics determine the power value E_{per}, and the temporal ones determine the duration t.

3 Results

We consider methods for assessing the characteristics of sensor networks, which are basic for solving all other problems. At the forefront is the assessment of the energy consumption of sensor devices for different strategies for delivering data from the sensor device to the head node of the cluster or to the base station in the volume of the sensor field (Fig. 1).

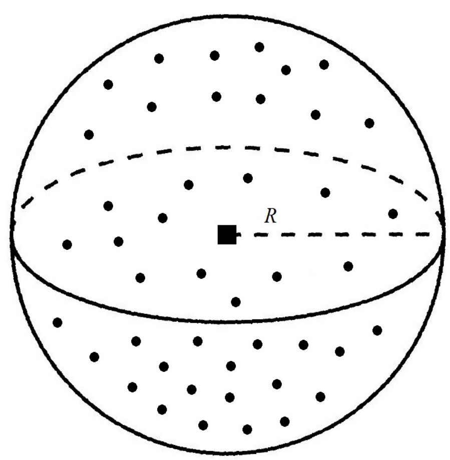

Fig. 1. Placing smart things in a ball space.

In a field, a garden, greenhouses, a farm, and other objects, sensors must monitor the state of soil, air, animals, climatic parameters, and technology, recording a huge number of various parameters [13].

In all cases, for the formation of a smart agricultural object, it is necessary to organize a network of a large number of sensor devices with autonomous power. To reduce the labor costs associated with replacing electric batteries, energy-saving modes of operation of sensors should be provided, therefore, the development of a model for evaluating the appropriate characteristics for the three-dimensional space of agricultural land is relevant and of practical importance [14].

The power consumption of devices and the network as a whole depends on the relay method. Geo-positioning allows you to determine the distance to each sensor device in the network.

The transmission of a data block directly to the base station without relaying is a special case of the methods considered.

Building models to estimate the average distances to all neighbors will allow you to find the average distance to an arbitrary sensor device.

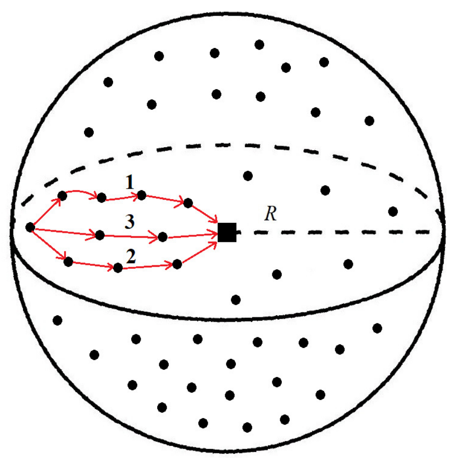

Fig. 2. Possible options for relaying data blocks (1. relay of the closest smart thing, 2. relay of the second closest smart thing, 3. relay of the third closest smart thing).

The required signal power at the transmitting antenna, assuming that the radio signal power at the receiving antenna is constant, is a random variable and depends on the distance between the interacting devices.

Therefore, the average power at the transmitter according to the Friis formula takes the form [15]:

$$\bar{E}_{per} = \frac{16}{27} \frac{\sqrt[3]{\pi^{10}}\sqrt[3]{2^2}\sqrt[3]{3^2} E_{pr} f^2}{\sqrt[3]{\lambda^2}\left(\Gamma\left(\frac{2}{3}\right)\right)^2 C_{per} C_{pr} {v_c}^2} \tag{11}$$

Where E_{per} is the average power of the radio signal at the transmitting antenna [W], E_{pr} is the constant power of the radio signal at the receiving antenna [W], C_{per} is the gain of the transmitting antenna, C_{pr} is the gain of the receiving antenna.

The total transmission time of the data block from the touch device to the base station depends on the number of hop and is determined by the expression [15]:

$$\bar{t} = \frac{(k+1)}{2f}\gamma b \tag{12}$$

b – the length of the transmitted blocks (bits), k – the number of transits (hop) that occur when using one sensor device to transit a data block transmitted by other sensor devices, γ – the intensity of the transmission of data blocks by one device.

Let us that the number of hopes in the direction of increasing to the nearest integer:

$$k = \left\lceil \frac{R}{2\bar{r}} \right\rceil = \left\lceil \frac{3}{4\sqrt[3]{\pi^2}} \sqrt[3]{2^2}\,\sqrt[6]{3}\Gamma\left(\frac{2}{3}\right) \sqrt[3]{\lambda}\, R \right\rceil \tag{13}$$

where R is the radius of the ball. Then the total time takes the form:

$$\bar{t}_1 = \frac{1}{2}\,\frac{\left(\left\lceil \frac{3}{4\sqrt[3]{\pi^2}} \sqrt[3]{2^2}\,\sqrt[6]{3}\Gamma\left(\frac{2}{3}\right) \sqrt[3]{\lambda}\, R \right\rceil + 1\right)\gamma\, b}{f} \tag{14}$$

The average energy spent on the transfer unit of the sensor device:

$$\bar{e} = \bar{E}_{per} \cdot \bar{t} \tag{15}$$

The final expression for calculating the average energy spent on transmitting a data block to the nearest object:

$$\bar{e}_1 = \frac{8}{27}\,\frac{\sqrt[3]{\pi^{10}}\,\sqrt[3]{2^2}\,\sqrt[3]{3^2}\left(\left\lceil \frac{3}{4\sqrt[3]{\pi^2}} \sqrt[3]{2^2}\,\sqrt[6]{3}\Gamma\left(\frac{2}{3}\right) \sqrt[3]{\lambda}\, R \right\rceil + 1\right) E_{pr}\gamma\, b}{\lambda^{\frac{2}{3}}\Gamma\left(\frac{2}{3}\right)^2 C_{per}C_{pr}v_c} \tag{16}$$

The average energy spent on transferring a block of the second smartest thing in distance:

$$\bar{e}_1 = \frac{128}{243}\,\frac{\sqrt[3]{\pi^{10}}\,\sqrt[3]{2^2}\,\sqrt[3]{3^2}\left(\left\lceil \frac{9}{16\sqrt[3]{\pi^2}} \sqrt[3]{2^2}\,\sqrt[6]{3}\Gamma\left(\frac{2}{3}\right) \sqrt[3]{\lambda}\, R \right\rceil + 1\right) E_{pr}\gamma\, b}{\lambda^{\frac{2}{3}}\Gamma\left(\frac{2}{3}\right)^2 C_{per}C_{pr}v_c} \tag{17}$$

The average energy spent on transferring the block to the third sensory object in distance:

$$\bar{e}_1 = \frac{1568}{2187}\,\frac{\sqrt[3]{\pi^{10}}\,\sqrt[3]{2^2}\,\sqrt[3]{3^2}\left(\left\lceil \frac{27}{56\sqrt[3]{\pi^2}} \sqrt[3]{2^2}\,\sqrt[6]{3}\Gamma\left(\frac{2}{3}\right) \sqrt[3]{\lambda}\, R \right\rceil + 1\right) E_{pr}\gamma\, b}{\lambda^{\frac{2}{3}}\Gamma\left(\frac{2}{3}\right)^2 C_{per}C_{pr}v_c} \tag{18}$$

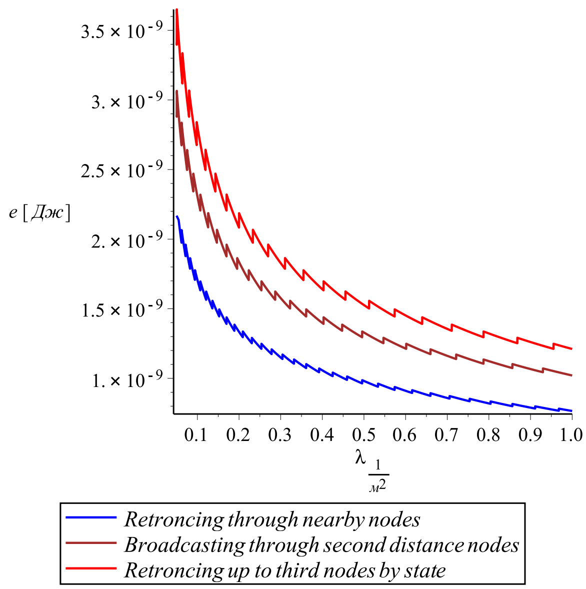

Fig. 3. The dependence of the energy consumption of sensor devices on the density of the sensor field

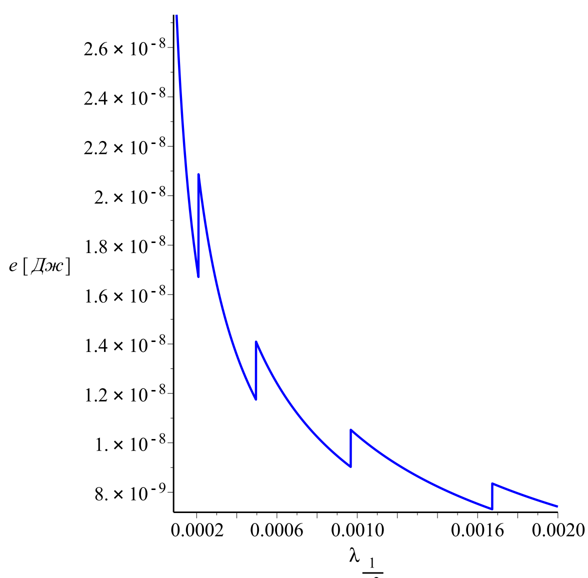

Fig. 4. Relaying the closest smart thing

Figure 3 shows the dependence of energy consumption on the distribution density of sensor devices in volume.

When relaying through the nearest nodes, an increase in the number of hopes occurs, but the energy is spent on transmission less since the energy consumption is proportional to the square of the distance (Fig. 3).

The spasmodic nature of the functions in Figures 3 and 4 is due to the rounding of the found hop values to the whole.

Table 1. The value of energy consumption of sensor devices from the density of sensor devices at signal frequency values, nJ.

The density of the sensor field λ, $\frac{1}{m^2}$	Signal frequencies f, Hz			
	$13.56 \cdot 10^6$	$40 \cdot 10^6$	$2.4 \cdot 10^9$	$5.5 \cdot 10^9$
0.1	1.71	5.03	302.2	692.2
0.2	1.33	3.93	236.1	541.1
0.3	1.15	3.39	203.4	466.1
0.4	1.06	3.11	187.1	428.8
0.5	9.81	2.89	173.6	397.9
0.6	9.1	2.68	161.1	369.1
0.7	8.58	2.53	151.9	348.2
0.8	8.19	2.41	145.1	332.4
0.9	7.89	2.32	139.7	320.1
1	7.65	2.25	135.4	310.3

Table 2. The value of the energy consumption of sensor devices from the transmission intensity of data blocks by one device with the length of the transmitted blocks, nJ.

Intensity of transmission of data blocks by one device γ, blocks/s	The length of the transmitted blocks b, bits				
	64	128	256	512	1024
0.1	0.38	7.61	1.52	3.04	6.08
0.2	0.76	1.52	3.04	6.08	12.17
0.3	1.14	2.28	4.56	9.13	18.26
0.4	1.52	3.04	6.08	12.17	24.34
0.5	1.9	3.81	7.61	15.21	30.43
0.6	2.28	4.56	9.13	18.26	36.52
0.7	2.66	5.32	10.65	21.31	42.61
0.8	3.04	6.08	12.17	24.34	48.69
0.9	3.42	6.84	13.69	27.39	54.78
1	3.81	7.61	15.21	30.43	60.87

The data in the tables represents the value of the spatial, temporal and energy characteristics, since the frequency and intensity is a temporal characteristic, and the density is a spatial characteristic.

4 Discussions

Energy consumption as one of the key issues for wireless sensor networks is analyzed in publications [16, 17]. In [16], it is proposed to solve the problem of increasing the lifetime of a wireless sensor network by controlling the energy balance of transceiving nodes that provide signal power correction based on the measurement results of the communication range and taking into account the characteristics of signal transmission in the radio channel and reception, and in [18] for to ensure maximum lifespan of the wireless sensor network, multi-path routing with support for energy balancing of nodes and.

In [3], when determining connectivity, it is proposed to take into account the spatial, temporal, and energy characteristics of wireless networks in a complex, and indicators and models are proposed for conducting corresponding quantitative assessments.

In [15], the presented material synthesizes an approach to the choice of information technologies that takes into account not only the quality of information interaction in a certain subject area, but also the volumes of required physical resources, and develops the results of modeling the process of interaction of devices of the Internet of things by determining the influence of probability-energy characteristics on energy consumption .

5 Conclusion

This study analyzes the features of the energy consumption process of wireless sensor networks in agricultural applications. The study allowed us to determine indicators for evaluating the energy consumption characteristics of sensor devices in three-dimensional space and to develop a model for evaluating these indicators.

The developed model for evaluating the characteristics of sensory devices in the three-dimensional space of smart things differs from the models considered in [15] in that the model allows us to consider areas in space, and not on a plane.

A numerical analysis of the energy consumption of wireless sensor networks has been performed. A method and model for a comprehensive assessment of spatial, temporal and energy characteristics are proposed. This method allows you to see how some data depends on others

References

1. Recommendation Y. 2060. Overview of Internet of Things. ITU-T, Geneva. June 20 [Electronic resource] access mode:https://www.itu.int/rec/T-REC-Y.2060-201206-I

2. Roslyakov, A.V., Vanyashin, S.V., Grebeshkov, A.Yu., Samsonov, M.Yu.: Internet of things. under the editorship of A.V. Roslyakova. Samara: PSUTI, LLC As Gard Publishing House, (2014)
3. Astakhova, T.N., Verzun, N.A., Kasatkin, V.V., Kolbanev, M.O., Shamin, A.A.: The study of connectivity models of sensor networks. Information Management Systems. **5**(102). pp. 38–50.(2019)
4. Digital Economy of the Russian Federation [Electronic resource] access mode: https://digital.ac.gov.ru/
5. Ventzel, E. S. Wentzel, E. S., Ovcharov, L. A.: Tasks and exercises in probability theory: Textbook. allowance for students. universities. 5th ed., Rev. M.: Publishing Center "Academy", (2003)
6. Kozhanov, Yu.F., Kolbanev, M.O.: Infocommunication Technology. Kursk: Naukom, (2011)
7. Bogatyrev,V.A., Vinokurova, M. S.: Control and Safety of Operation of Duplicated Computer Systems. Communications in Computer and Information Science, IET Vol. 700, pp. 331-342 (2017)
8. Bogatyrev, A.V., Bogatyrev, S.V., Bogatyrev, V.A.: Analysis of the Timeliness of Redundant Service in the System of the Parallel-Series Connection of Nodes with Unlimited Queues. In: 2018 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF), (2018).
9. Galkin, P.V.: Energy analysis of nodes of wireless sensor networks. Scientific Journal "ScienceRise" **2**(2). pp. 55-61. (2014)
10. Galkin, P. V., Karlovsky, D. V.: Features of realization of off-wire sensory networks on the basis of technology of ZigBee. VII Miedzynarodowej naukowipraktycznej konferencji Nauka i inowacja-2011. 31. pp. 7–11.(2010)
11. Shaw, J. A.: Radiometry and the Friis transmission equation. American journal of physics **81**(1), pp. 33-37 (2013). https://doi.org/10.1119/1.4755780
12. Wallace, R.: Maximum communication range over a radio channel in a system: how to achieve this? Electronics News 11. pp. 3-13(2015)
13. Kolbanev M.O., Romanova A.A.: On the construction of a smart field. Prospective directions for the development of domestic information technology materials of the IV interregional scientific and practical conference. Sevastopol State University; scientific ed. B.V. Sokolov. pp. 77-78. (2018)
14. Bogatyrev, A.V., Bogatyrev, V.A., Bogatyrev,S.V.: "Multipath Redundant Transmission with Packet Segmentation," 2019 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF), Saint-Petersburg, Russia. 2019. pp. 1-4. https://doi.org/10.1109/WECONF.2019.8840643
15. Astakhova, T.N., Verzun, N.A., Kolbanev, M.O., Polyanskaya, N.A., Shamin A.A.: Probabilistic-energetic characteristics of the interaction of smart things. Bulletin of the NIIEI **4**(95). pp. 66–7 (2019)
16. Shostko, I.S., Kulya, Yu. E. A.: method for increasing the lifetime of an autonomous wireless sensor network through the use of energy-efficient transmitter operating modes. Problems of Telecommunications. **1**(16). pp. 3–15. (2015)
17. Voskov, L.S., Komarov, M.M.: Energy balancing method for a wireless stationary sensor network with autonomous power sources. Business Informatics. **1**(19). pp. 70—75. (2012)
18. Shostko I.S., Kulya Yu. E. Development of a routing model of a wireless sensor network taking into account the elimination of an imbalance in energy consumption. Technological audit and production reserves. **3/2**(23). pp. 94-–98. (2015)