A model for estimating energy consumption seen when nodes of ubiquitous sensor networks communicate information to each other

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Abstract. A model for calculating the total energy consumption for the implementation of information interaction processes of nodes via radio networks, which allows to evaluate the ecological compatibility of the network and manage its lifetime, is developed on the basis of data on the distribution in space of sensor nodes organized in accordance with the mesh topology. The probability distribution functions of the random value of the power of the radiating antenna of the sensor device, sufficient for transmitting the data block to the receiving side, and the total energy consumption of this network during information interaction are obtained. A mathematical model of the physical process of information interaction in the sensor network in the case of a Poisson field of points and for different variants of retransmissions – the first, second, fourth and n-th "neighbor" is built. Numerical calculation and analysis of the influence of the parameters of the considered ubiquitious sensor network and nodes on the required radio signal power at the transmitting antenna of the object are conducted. The presented material develops the results of modeling the interaction process of Internet of Things devices by determining the impact on energy consumption of probability-energy characteristics. The study allowed to determine the interdependence of energy and information parameters of the sensor network. The constructed model will allow to estimate the lifetime of the sensor network. A possible development of the presented research may be the development of routing protocols that use the assessment of energy consumption by sensory devices.

Keywords: Distribution density · Energy costs · Energy efficiency · Environmental friendliness of the network · Internet of Things · Poisson field of points · Probability-energy characteristics · Sensor nodes · Ubiquitous sensor network

1 Relevance

Information systems have an increasingly greater impact on the Earth's environment. It is already the case that roughly a third of electricity generated globally is consumed by back-end devices, routers, and infocommunication networks' data processing centers, while electricity generation capacity of big cities and smaller towns is becoming the main stumbling block to introducing digital economy technologies [1, 2].

The fundamental principle that is recommended by the International Telecommunication Union to be followed when creating 5G networks or Future Networks (FN) is the principle of environmental sustainability [3], according to which it is required to implement technical solutions that reduce energy consumption in order to make FN environmentally-friendly.

One of the most powerful consumers of electricity is the Internet of Things, whose terminals are self-powered smart things (sensor-equipped devices) interacting with each other via radio networks. Increased lifetime of this type of network directly depends on saving battery power of sensor-equipped devices, while battery power is mainly consumed by radio transmitters, which require about a million times more energy to transmit one bit of information compared to the power used when the bit is processed by a processor.

A need to make infocommunication networks more environmentally sustainable coupled with a need to increase the lifetime of sensor-equipped devices by saving energy of their batteries have both determined the relevance of the conducted study, whose results can be applied when developing methods for managing energy consumption on the Internet of Things.

2 Methods

ITU-T Recommendation Y.3021 identifies three levels (for devices, equipment, and the network as a whole), any of which requires specific energy-saving technologies to be developed [4]. At the network level, energy saving can be facilitated not only by the rational choice of parameters for information flow control protocols such as the length of transmitted blocks, a way to route packages through the network, an algorithm for media access, a method for error-control coding of transmitted blocks, data compression, data encryption, etc. but also by power control of sensor-equipped device's radio transmitter [5]. With the distance between the interacting sensors reduced, the power can be adjustably reduced; conversely, with the distance between the interacting sensors increased, it can be increased. Respective mechanisms have been implemented in a number of existing radio networks.

In this case, total expenditure of electricity in the network with the appropriate protocols does not only depend on how intensely information is transmitted between the terminals, but also on how dense the sensory field is and which criterion has been used for selecting the transit node.

The purpose of this paper is to develop a model for estimating the total energy consumption required for organizing information-based interaction between sensor network nodes that depends on spatial network parameters as well as technical parameters of sensor-equipped devices, since this indicator is the one that characterizes ecological compatibility of the network during its operation and gives insight into the network lifetime as a whole.

The subject under investigation is a ubiquitous sensor network, which is a set of sensor-equipped smart things connected with each other and with a cloud, where measurement of physical parameters of the environment is ensured by the sensors.

It is assumed that the sensor network has a cellular (or mesh) topology and, at the data link layer, provides direct communication between neighbors within the radio range, whereas communication between the other elements is ensured with relays. A coordinator can be used to communicate with the outside environment.

The sensory network is characterized by the size of the sensory field and the number of smart things located in this space. Unlike the coverage area of infrastructure networks, the sensor field can change linear dimensions which depend on random relocation of smart things; be two-dimensional and three-dimensional, accommodate the changing number of smart things that require integrated management.

Examples of the sensory field include but are not limited to the following: the territory of a settlement, a monitoring system for aroma safety in a certain area [6, 7], an agricultural farm, a body or part of a human body in medicine, an oil rig in the extractive industry, etc.

All the other spatial characteristics depend on the size (the area or the volume) of the sensory field as well as the number of smart things put together.

The field of points which are randomly distributed in space is chosen as a model of the sensory field, with the main characteristic being density of the field measured by an average number of points per unit of the area (volume). A sensory field consisting of homogeneous sensors is looked into, where:

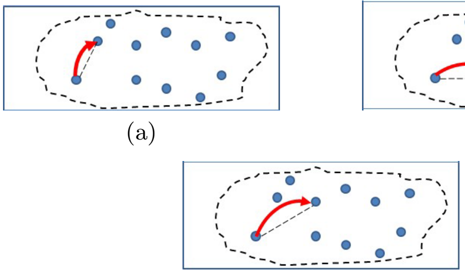
- the probability of occurrence of any given number of points in any area of the surface does not depend on how many points fall into any areas that do not intersect with this one;
- the probability of hitting the elementary region of two or more points is negligible compared to the probability of hitting a single point.

Such a sensory field can be described by a Poisson field of points.

These conditions have enabled us to obtain probability distribution functions of the random power value of the radiating antenna on the sensor-equipped device, sufficient for transmitting the data block to the receiving side, and the total energy consumption of this network while communicating data.

3 Results

According to the currently used routing protocols of the ubiquitous sensor network, there are various options for retransmitting data blocks when transmitting from a smart thing to base station: the first, second, and so on “neighbor” (Fig. 1).



(a) (b) (c)

Fig. 1: Possible options for hops: (a) retransmission to the nearest sensor node; (b) retransmission to the second closest sensor node; (c) retransmission to the third nearest sensor node.

We construct a mathematical model of the physical process of information interaction in the sensor network in the case of a Poisson field of points (sensor nodes) and for different versions of retransmissions of the data blocks to the first, second, fourth and n-th neighbor.

The number of points (m) of a uniform Poisson field on a plane with density ν on a sufficiently large circle of radius R. The distribution function of the distance between sensor nodes obeys the Poisson law

$$F_m = \frac{a^m}{m!} e^{-a} \tag{1}$$

where a is the mathematical expectation of the number of points falling into the domain S $[m^2]$.

The distribution function of the distance between points of a uniform Poisson field of points on the plane obeys the Rayleigh law: for the nearest “neighbor” (sensor node), the distribution law is

$$F_1(r) = 1 - e^{-\pi r^2 \nu} \tag{2}$$

where does the distribution density of the random variable r

$$f_1(r) = 2\pi\nu r e^{-\pi r^2 \nu} \tag{3}$$

Then the average distance to the nearest sensor node is calculated by the formula

$$\overline{r} = \int_0^\infty r \cdot f_1(r) dr = \int_0^\infty r \cdot 2\pi\nu r e^{-\pi r^2 \nu} dr = \frac{1}{2\sqrt{\nu}} \tag{4}$$

According to the Friis transmission equation, the radio signal power at the transmitting antenna of the object of the wireless sensor network is determined as follows:

$$P_t = \frac{16 P_r \pi^2 r^2}{C_r C_t \gamma^2} \tag{5}$$

where γ is the wavelength [m] of the transmitted radio signal, C_t is the isotropic directivity of the transmitting antenna in the direction of the receiving antenna, C_r is the isotropic directivity of the receiving antenna in the direction of the transmitting antenna, P_t is the power delivered to the terminals of an isotropic transmit antenna [W] (excluding losses), P_r is the power available at receiving antenna [W] (excluding losses), r – distance between the antennas of sensor network objects [m]. The required signal power at the transmitting antenna P_t, under the assumption that the radio signal power at the receiving antenna P_r is constant, a random variable depending on the distance between the interacting objects.

The wavelength is related to the frequency of the signal flow

$$\gamma = \frac{c}{f} \tag{6}$$

where c – speed of light ($\sim 3 \cdot 10^8 [m/s]$).

Substituting γ in the Friis equation, we obtain the radio signal power at the transmitting antenna in the form:

$$P_t = \frac{16 P_r \pi^2 r^2 f^2}{C_r C_t c^2} \tag{7}$$

The average power is found by substituting the average distance:

$$\overline{P}_t = \frac{4 P_r \pi^2 f^2}{\nu C_r C_t c^2} \tag{8}$$

The total transmission time of all data blocks is $\overline{t} = \Lambda \cdot \tau$, where τ is the activity time of a smart object when transmitting one block, Λ is the total transmission intensity of all blocks.

The total intensity with regard to transits is $\Lambda = (k+1) \cdot \lambda$, where k is the number of hopes, λ is the blocks transmission rate.

The channel speed at frequency f according to the Nyquist formula is $2f [bit/s]$, and then the activity time τ is calculated as $\tau = \frac{b}{2f}$, where b is the length of the transmitted blocks (bit).

The number of transits (hopes) will be taken upwards to the nearest integer

$$k = \left\lceil \frac{R}{2 \cdot \overline{r}} \right\rceil \tag{9}$$

Then the total time takes the form

$$t = \frac{\lceil R\sqrt{\nu} + 1 \rceil \lambda b}{2f} \tag{10}$$

The average energy spent on the transfer of the block smart things

$$\overline{e} = \overline{P_t} \cdot t \tag{11}$$

Therefore, for transfer information to the nearest object is calculated as follows

$$\overline{e_1} = \frac{2P_r\pi^2 f\lambda b\left(\lceil R\sqrt{\nu}\rceil + 1\right)}{\nu C_r C_t c^2} \tag{12}$$

The average energy spent on the transfer of the second block of the distance of a sensor node

$$\overline{e_2} = \frac{9P_r\pi^2 f\lambda b\left(\lceil \frac{2}{3}R\sqrt{\nu}\rceil + 1\right)}{2\nu C_r C_t c^2} \tag{13}$$

The average energy spent on the transfer of the block to the fourth sensory object

$$\overline{e_4} = \frac{1225P_r\pi^2 f\lambda b\left(\lceil \frac{16}{35}R\sqrt{\nu}\rceil + 1\right)}{128\nu C_r C_t c^2} \tag{14}$$

Consider the case when information is transmitted to the n-th sensor node. In this case, the Rayleigh's law will be as follows

$$F_n(r) = 1 - \sum_{k=0}^{n-1} \frac{(\pi r^2\nu)^k}{k!} e^{-\pi r^2 \nu} \tag{15}$$

or

$$F_n(r) = 1 - \frac{\Gamma(n, r^2\nu)}{\Gamma(n)} \tag{16}$$

where $\Gamma(n) = \int_0^\infty e^{-t}t^{n-1}dt$, and $\Gamma(n, r^2\nu) = \int_{r^2\nu}^\infty e^{-t}t^{n-1}dt$.

Distribution density of a random variable r

$$f_n(r) = \frac{\Gamma\left(n + \frac{1}{2}\right)}{\sqrt{\pi}\sqrt{\nu}\Gamma(n)} \tag{17}$$

and the average energy that is required to transfer b bits of information of the n-th is

$$\overline{e_n} = \frac{8P_r\pi\Gamma\left(n + \frac{1}{2}\right)^2 f\lambda b\left(\left\lceil \frac{R\sqrt{\pi}\sqrt{\nu}\Gamma(n)}{\Gamma\left(n+\frac{1}{2}\right)}\right\rceil + 1\right)}{\nu\Gamma(n)^2 C_r C_t c^2} \tag{18}$$

4 Numerical calculation

Using the above expressions, we carried out a numerical calculation and analyzed the effects of the parameters of the considered wireless sensor network and sensor nodes on the required radio signal power at the transmitting antenna of the wireless sensor network object.

Suppose that when a block is transmitted along a route, when choosing a transit smart thing, the nearest "neighbor" is selected with probability p and the fourth neighbor with probability $(1-p)$. Then the energy expended on the transfer unit

$$\overline{e_{gen}} = \overline{e_1} \cdot p + \overline{e_4}(1-p) \tag{19}$$

$$\overline{e_{gen}} = \frac{2P_r\pi^2 f\lambda b\left(\lceil R\sqrt{\nu}\rceil+1\right)}{\nu C_r C_t c^2}p + \overline{e_4} = \frac{1225P_r\pi^2 f\lambda b\left(\lceil \frac{16}{35}R\sqrt{\nu}\rceil+1\right)}{128\nu C_r C_t c^2}(1-p) \tag{20}$$

At values $c = 3\cdot 10^8$m/s, $C_t = 1$,$C_r = 1$, $P_r = 0.1\cdot 10^{-3}$W, $R = 56$m, $f = 13.56\cdot 10^6$Hz, $b = 64$ bits, $\lambda = 1$ block/s, $\nu = 0.01\frac{1}{m^2}$ (see Fig. 2):

$$\overline{e_{gen}} = -1.17\cdot 10^7 p + 2\cdot 10^7 [J] \tag{21}$$

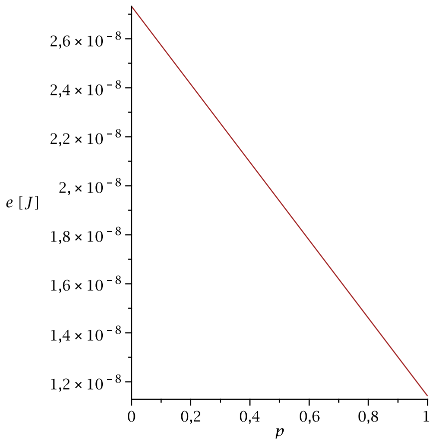


Fig. 2: The dependence of energy consumption on the probability of choosing a transit option.

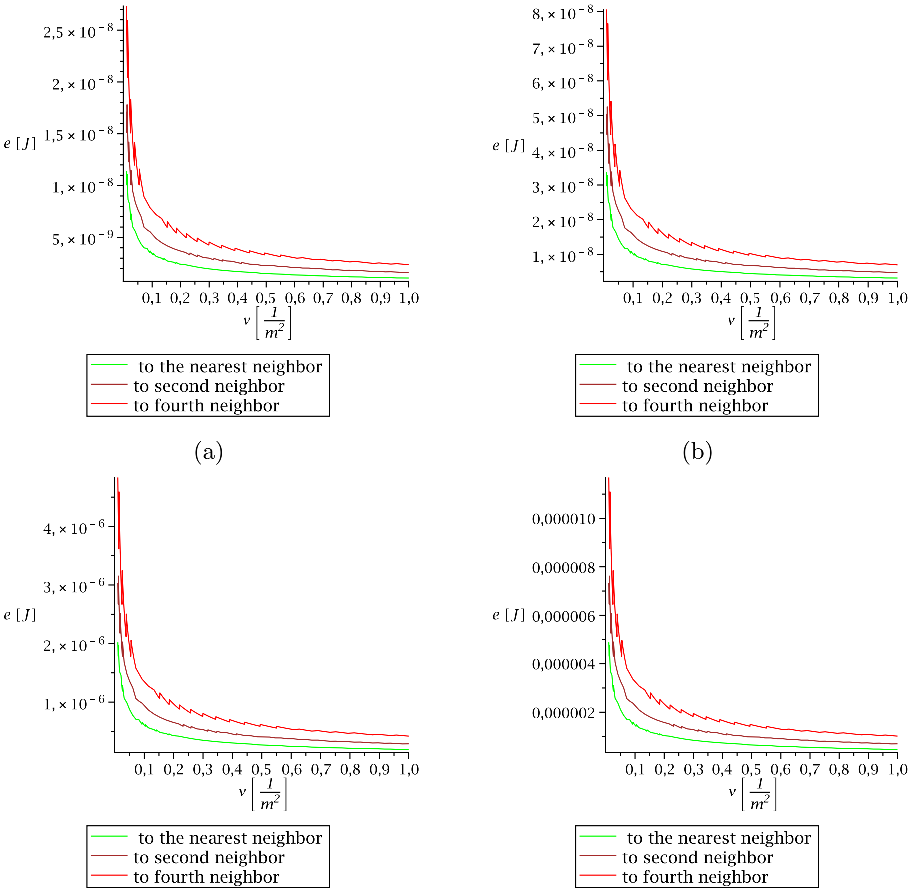
The influence on the energy consumption of a sensor node of the following parameters of ubiquitious sensor network: the density of distribution of smart things in the network (ν), length (b) and intensity (λ) of transmitted blocks, radio frequency (f), transit option is also considered in the article.

The dependence of energy consumption on the distribution density of sensor nodes on a plane with different transmission options for different signal frequency values is presented in Figure 3.

Figure 4 shows the dependence of energy consumption on the length of the transmitted blocks with the signal frequency $f = 13.56\cdot 10^6$ Hz, the intensity of the transmitted blocks $\lambda = 1$ block/s, and the density of the distribution $\nu = 0.01\frac{1}{m^2}$.

The dependences of energy consumption on the intensity of the message appearance and on different values of the frequency with the length of the transmitted blocks $b = 64$ bits and the distribution density $\nu = 0.01\frac{1}{m^2}$ are presented in Figures 5 and 6, respectively.

Thus, in the paper, the probability distribution function of the random power values of the radiating antenna on the sensor-equipped device, which provides the possibility of a stable information communication, has been obtained.



(a) (b)

(c) (d)

Fig. 3: Dependence of energy consumption on the density of sensor nodes at signal frequencies:
(a) $f = 13.56 \cdot 10^6$ Hz, (b) $f = 40 \cdot 10^6$ Hz,
(c) $f = 2.4 \cdot 10^9$ Hz, (d) $f = 5.8 \cdot 10^9$ Hz.

Influence of the spatial parameters of the sensor network on its total energy consumption for various frequency ranges has been evaluated.

Recommendations are made regarding development of procedures for selecting routes in mesh networks according to the criterion of energy saving.

5 Discussion

When communication networks created in the twentieth century had been designed, correlations between their space-, time-, and energy-related character-

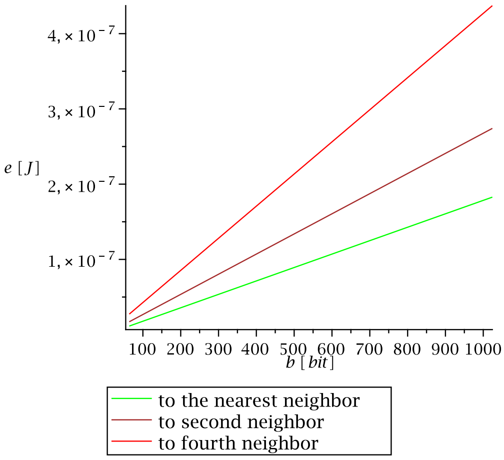


Fig. 4: Dependence of energy consumption on the length of the transmitted blocks.

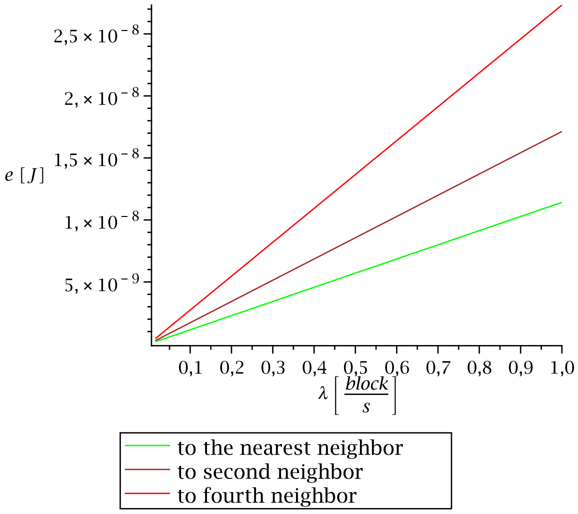


Fig. 5: The dependence of energy consumption on the intensity of the blocks appearance.

istics were not taken into account, while performance quality indicators were described using probabilistic-temporal characteristics such as the probability distribution functions of data transfer times from the information source to the communication channel, transmission of the signal via channels between network centers, control of signal moving in network centers or their components [8].

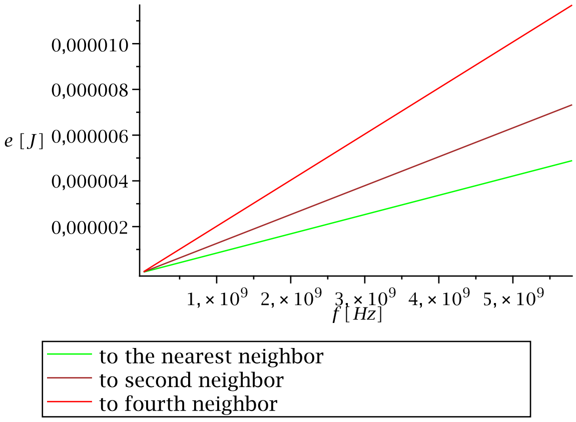


Fig. 6: The dependence of energy consumption on the frequency of the radio signal.

Another kind of indicators are network reliability indicators [9]. An example of research where a redundant distribution of requests is proposed in order to improve reliability of transmission in a network with additional energy expenditure for such interaction not having been taken into account, can be found in the article [10].

In modern networks, such as FN or the Internet of Things, the mutual dependence of physical parameters can no longer be neglected. The results obtained in this paper confirm this statement and allow us to quantitatively compare the correlation between the quality of service measured using the probability-time characteristics with the energy consumption that ensures this quality.

The presented material specifies the results of the study [11], in which a general approach to selection of information technologies has been worked out for the first time. In addition to the quality of information interaction in a particular subject area, the approach also takes into account the amount of physical resources required. Moreover, the paper elaborates on the results of work [12], where simulation of the interaction process between IoT devices has been carried out with the impact of the physical and data link layer protocols on the power consumption taken into account.

6 Conclusion

This study looks into probabilistic and energy characteristics, which also depend on the network parameters of the network layer protocol apart from physical and data link layer ones. It is proposed to add probabilistic and energy characteristics, which depend on the spatial parameters of the network as well as technical characteristics of sensor-equipped devices, to the previously used indicators for network performance assessment.

The presented research may be followed up by an attempt to design routing protocols that use estimation of energy consumption by sensor-equipped devices.

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