Estimation of Energy Costs for Priority Maintenance of Mobile Devices of the Ubiquitous Sensor Network

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Abstract. The object of study is the ubiquitous sensor network of mobile devices. The energy consumption model for servicing in the discipline of relative priorities is the subject of research. The purpose of this work is to build a model of priority service for mobile devices, in accordance with which, those sensor nodes that are located near the base station receive a relative priority in service. With this approach, it is likely that the remote sensor devices during the polling of the nearest ones will also enter the priority service area, which, in turn, will reduce energy consumption when transferring a data block from some mobile sensor device to the base station. To build the model, it is necessary to use a comprehensive technique: the first part of the model allows us to estimate the probability-time characteristics of the process of delivery of information data blocks from sensor devices to the base station; the second part of the model is designed to estimate the total energy consumption of sensor devices. It is assumed that at each moment of time, the sensor devices are distributed on the sensor field in accordance with the Poisson law. A numerical calculation and analysis of the influence of spatial and time characteristics on the energy consumption of mobile sensor devices of a ubiquitous sensor network is carried out.

Keywords: Distribution density · Energy costs · Energy efficiency · Poisson field of points · Probability-energy characteristics · Sensor devices · Ubiquitous sensor network

1 Introduction

One of the most popular and widespread methods of collecting and transmitting data is ubiquitous sensor networks [1–7]. The ubiquitous sensor network is a network of intelligent sensors, including mobile sensor devices, which can change their location within the sensor field. If the sensor field is equipped with one base station, then the sensor devices during the movement can be either closer to it or further.

An important characteristic of ubiquitous sensor networks is the amount of power consumption by self-powered sensor nodes. [8–11]. It is advisable to receive information in the form of data blocks at those moments when they are closer to the base station [12, 13].

A significant part of energy costs is associated with the information interaction of sensor devices with a base station. Moreover, the closer the sensor device is to the base station, the less energy it spends when transmitting an information block [14].

Consider the following algorithm for the interaction of sensor devices with a base station. Assume that the process of transmitting data from sensor devices consists of two stages. First, the mobile touch device informs the base station with a short message that it is ready to transmit data. Then, on command from the base station, it transmits the generated block. The base station knows in which part of the sensor field each sensor device is located.

On the other hand, the bandwidth of the base station is usually such that in order to receive information from sensor devices, it cannot wait for a particular device to get close enough to it. At the same time, in each polling cycle of sensor devices, the base station should interact with all devices, and not just those in the immediate vicinity.

Therefore, the base station can use the service discipline with relative priorities. A higher first priority will be given to mobile sensor devices located in the near part of the sensor field.

Purpose of work is building a model of priority service for mobile devices, in accordance with which, those sensor nodes that are located near the base station receive a relative priority in service. With this approach, it is likely that the remote sensor devices during the polling of the nearest ones will also enter the priority service area, which, in turn, will reduce energy consumption when transferring a data block from some mobile sensor device to the base station.

The object of study is the ubiquitous sensor network of mobile devices. The subject is the model of energy consumption in servicing in the discipline of relative priorities.

Tasks to be solved:

1. Analysis of data acquisition modes of sensor devices within the cluster.
2. Construction of a mathematical model that establishes the dependence of energy consumption on the distribution function of sensor devices across the sensor field.
3. Conducting numerical experiments of the constructed model.

A very general approach to the formation of the process of separation of time resources of the base station ("processor separation mode" according to Kleinrock) between the interrogated sensor devices forming a cluster is proposed.

It is based on a model for moving sensor devices in the space of a sensor field; assigning higher relative priorities to those sensor devices that require less energy to deliver data.

2 Methods

To build a model, it is necessary to solve several interrelated tasks. The proposed model consists of two parts. The first part of the model allows us to estimate the probabilistic-time characteristics of the process of delivery of information data blocks from sensor devices to the base station. For this, queuing models M/G/1 with relative priorities are used. The desired probability of aging information generated by sensor devices is estimated by the method described in the article [15], based on the Laplace-Stieltjes transform of the residence time for each of the relative priorities.

The second part of the model is designed to estimate the total energy consumption of sensor devices. For this, the approach developed in the works is used [16–18].

At the same time, it is assumed that at each moment of time, the sensor devices are located on the sensor field in accordance with the Poisson law.

2.1 Priority mode of data collection from sensor devices of some cluster

Suppose that sensor devices receive service priorities depending on the distance from the base station (see. Fig 1).

Algorithm for the interaction of sensor devices with a base station.

1. Informing the base station from the mobile sensor device with a short message about the readiness to transmit data.
2. Command transmission from the base station of the formed block.

For the queuing model M/G/1, the input flux for service to the system is a Poisson flow, in the system there is a single-channel serving device and an arbitrary distribution of the service time. The input Poisson flux has an intensity of λ. The service device is represented by an k-th order Erlang flow generator – in the form of a Markov chain sequence with some intensity of transitions between states.

The flow of applications is formed by packages that need to be transferred (serviced), service is the transmission of a packet. The residence time of an application in the system consists of the waiting time in the device buffer and the mediocre service time (packet transmission, data block).

Relative priorities play a role in the selection of applications from the queue. At the time of selection, the priorities of applications that are pending are compared, and service is provided to the application with the highest priority (with increasing number, priority decreases, that is, the highest priority is the first).

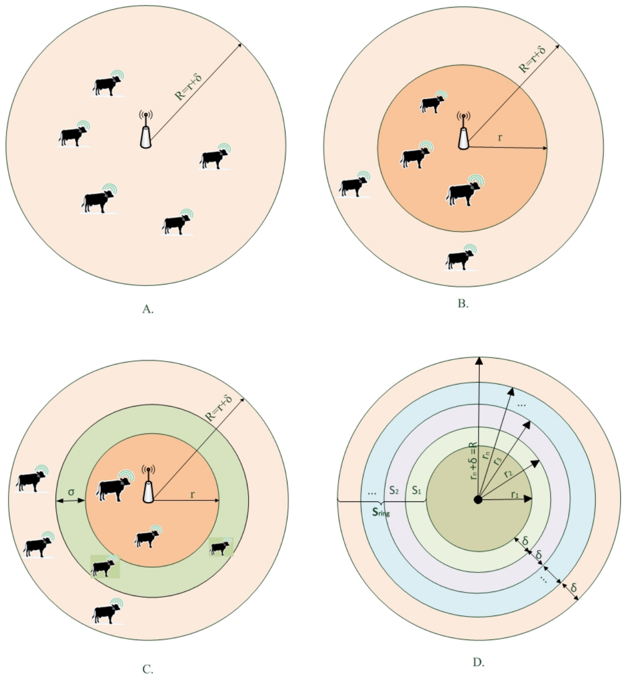

Fig. 1: Possible types of separation of the sensor field.

If in the process of servicing an application claims with higher priorities arrive, the servicing of the current application is not interrupted, and the received applications are sent to the queue.

Under the conditions described in [15], the following expressions are valid for the probability-time characteristics of the service process.

The main characteristics of this system are the Pollachek-Khinchin formulas. The average delivery time for the M/G/1 system is determined by the access control protocols for the control elements to the transmission medium and logical channel control and the parameters of the physical layer and transmission medium:

$$\omega_h^d(s) = \frac{s(1-\rho)g(e^{sT})}{s+\lambda(g(e^{sT})-1)} \tag{1}$$

where λ – input flow rate, ρ – flow loading, T – time parameter, $g(e^{sT})$ – Laplace-Stieltjes transform of the service interval distribution function.

The Laplace-Stieltjes transform of the time distribution function $t_h(s)$ of the service delivery process in response to the transmission of a data block with relative priority h is expressed as

$$t_h(s) = \omega_h^{proc}(s)\beta_h(s)\omega_h^d(s) \tag{2}$$

where $\omega_h^{proc}(s)$ and $\beta_h(s)$ are the Laplace-Stieltjes transform, respectively, of the distribution function of the waiting time for the start of processing and the processing time of a data block with priority h.

For $\omega_h^{proc}(s)$ expressions are

$$\omega_h^{proc}(s) = \frac{(1-\rho)G_h(s) + \sum_{j:h_j>h} \lambda_j[1-\beta_j(G_h(s))]}{s - \sum_{j:h_j=h} \lambda_j[1-\beta_j(G_h(s))]} \quad (3)$$

$$G_h(s) = s + \sum_{j:h_j<h} \lambda_j[1-\beta_j(G(s))] \quad (4)$$

where $\rho = \sum_i \rho_i$ – loading base station; λ_i – rate of data blocks with priority j.

When modeling an ubiquitous sensor network, the probability of timely delivery of a data block from the sensor device to the base station (P_s) can be estimated as follows:

$$P_s = 1 - \sum_{r=1}^{n} \eta_r \sum_{i=0}^{k-1} (-1)^i \frac{s_0^i}{i!} t^{(i)}(s_0) \quad (5)$$

where $s_0 = kv$, $t^{(i)}(s_0)$ – the value of the i-th derivative of the Laplace-Stieltjes transform of the service distribution time distribution function at the point s_0, k, v, η_r – are the Erlang distribution parameters.

2.2 Energy consumption of sensor devices

Make the following assumptions:

- the sensor field is a circle in the center of which is the base station;
- sensor devices move within this circle, but at each moment of time are distributed over the sensor field in accordance with Poisson's law.

Divide the field into n parts, as shown in the figure 1(D): base station workshop (radius r) and by outer diameter (radius $r+\delta$, where $\delta > 0$), etc.

The number of inner rings is $n = \frac{R-r}{\delta}$, $R > r > 0$, $\delta > 0$.

If δ is a sufficiently small quantity, then we can assume that the distance to all points of the Poisson field that are inside the i-th inner ring is

$$r_i = r + i \cdot \delta$$

In order to determine the average number of points of the Poisson field that are inside the i-th ring, it is necessary to know its inner and outer radius. The following formulas are valid for it:

$$l_i = r + (i-1)\cdot\delta, \quad L_i = l_i + \delta$$

The area of the i-th ring is

$$S_i = \pi\delta((2i-1)\delta + 2r)$$

By the Poisson formula, the average number of points that are located in the i -th inner ring is

$$N_i = S_i \cdot \nu$$

where S_i is the area of the i-th ring, ν is the distribution density of mobile sensor devices.

The probability that the n-th mobile sensor device is in a circle of radius r

$$F^n_{circ}(r) = P(R < r) = \frac{\Gamma(n) - \Gamma\left(n, \pi r^2 \nu\right)}{\Gamma(n)}$$

where $\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} dt$, $\Gamma(a, z) = \int_z^\infty e^{-t} t^{a-1} dt$.

The probability that the moving unit will be in the ring is calculated by the formula:

$$F^n_{ring}(r) = \frac{\Gamma\left(n, \pi\ (r+\delta)^2\, \nu\right) - \Gamma\left(n, \pi r^2 \nu\right)}{\Gamma(n)}$$

The average energy spent on the transmission of a data block by a sensor device will be calculated as:

$$\bar{e} = \bar{P}_{tr} \cdot \tau \tag{6}$$

where $\bar{P}_{tr}$ – is the average power [W] required for transmission.

Examples of realistic distance forecasts are considered on the basis of a two-beam model of propagation of radio waves according to the formula of Friis (Harald Friis) [19–22]. Due to the fact that the problem being solved, presented in this article, is devoted to the study of the interaction of sensor devices operating on agricultural land, we assume that transmission occurs in a homogeneous environment in the absence of obstacles, reflections, interference, and other factors affecting the distribution and reception signal (which is more typical of urban buildings). According to the equation for transmission, the power P_{tr} with a known degree of approximation can be converted to the circle radius – r [m], within which a sensor device can be selected for transit of the data block:

$$P_{tr} = \frac{16 P_r \pi^2 r^2 f^2}{C_{tr} C_r c^2}$$

where C_{tr} is the gain of the transmitting antenna, C_r is the gain of the receiving antenna, P_{tr} is the radio signal power at the transmitting antenna [W], P_r is the power of the radio signal at the received antenna [W], r is the distance between the antennas of the mobile sensor devices of the ubiquitous sensor network in meters, c is the speed of light, f is signal flow frequency.

It follows from the Friis formula that reducing the distance between two mobile sensor devices by 2 times reduces the energy consumption for transmitting a data block from one to another by 4 times.

Suppose that the average energy consumption of the network is all the average energy consumption for all points located within a given area.

The average energy spent on transmitting one data block to the base station from a sensor device located inside a circle of radius r is denoted by:

$$\bar{e}_c = \bar{P}_{circ} \cdot \tau_c \tag{7}$$

The average energy spent on transmitting one data block to the base station from a sensor device located inside the i-th ring will be found as:

$$\bar{e}^i_{ring} = \bar{P}^i_{circ} \cdot \tau_i \tag{8}$$

The total energy will be calculated as follows:

$$\bar{e} = \bar{e}_c + \sum_i \bar{e}^i_{ring} \tag{9}$$

The average number of sensor devices polled per cycle can be expressed as

$$N = N_c + \sum_i N_i \tag{10}$$

where N_c is the number of devices in a circle of radius r, N_i is the number of sensor devices in the i-th ring, $i = \overline{1, n+1}$.

To get the average power needed to transfer a data block from one sensor device located in the inner circle ($\bar{P}_{circ}$) or in the ring ($\bar{P}_{ring}$) of base station, it is necessary to calculate the power according to the Friis formula with average values of the distances from the sensor device to the base station for the circle and ring, respectively.

3 Results

Consider the case when the sensor field is divided into two parts: around the base station (circle of radius r) and the ring (external radius $r + \delta$, where $\delta > 0$) (Fig. 2(A)), and suppose that the sensor devices can move closer to the base station, for example, in a circle of radius $r - \sigma$, $\sigma \geq 0$ (Fig. 2(B)).

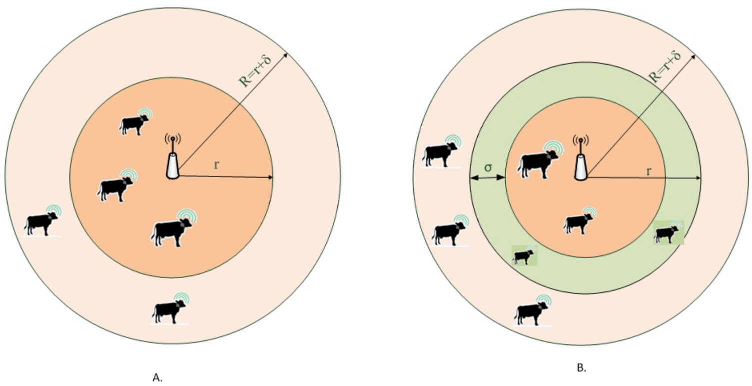

Fig. 2: Sensor field with mobile smart things.

The average energy spent transmitting one data block to the base station from a sensor device inside a circle of radius r:

$$\bar{e}_c = \frac{16P_r\pi^2r^2f^2}{C_trC_rc^2}\tau \qquad (11)$$

The average energy spent transmitting one block of data from a sensor device inside a large circle of radius $r+\delta$:

$$\bar{e}_R = \frac{16P_r\pi^2(r+\delta)^2f^2}{C_trC_rc^2}\tau \qquad (12)$$

The average energy spent transmitting one data block to the base station from a sensor device inside the ring:

$$\bar{e}_{ring} = \frac{4P_r\pi^2\left(r+\frac{\delta}{2}\right)^2f^2}{C_trC_rc^2}\tau \qquad (13)$$

The total energy spent on the transfer of one data block to the base station from all devices inside a large circle:

$$\bar{e}_{\tilde{R}} = \frac{16\pi^3P_r}{C_trC_rc^2}(r+\delta)^4f^2\nu\tau \qquad (14)$$

Then the total energy excluding the transition:

$$\bar{e}_{c+ring} = \frac{4\pi^3P_r}{C_trC_rc^2}\left(\delta^4+6\delta^3r+12\delta^2r^2+8\delta r^3+4r^4\right)f^2\nu\tau \qquad (15)$$

When setting priority service, we strive to read information from sensor devices that enter the inner circle. The probability of this event will be denoted as F_{rc}. Then the proportion of things in the inner circle will increase according to the proposed probability.

Introduce a priority survey of things that are in a certain area. At the beginning of the polling cycle, data is received from sensor devices that are inside a circle of radius r, and only then from devices that are in the ring.

The duration of one polling cycle is ζ. By $\zeta_{circ} = \sum_{i=1}^{N_{circ}}\zeta_{circ}^i$ we denote the time spent polling devices from the inner circle. During this time, ζ_{circ} with probability F_{rc} the sensor device from the ring will move inside the small circle. This means that the average number of points in a circle of radius r will increase by this probability times the average number of points in the ring, i.e. $F_{rc} \cdot S_{ring} \cdot \nu$.Therefore, the average number of touch devices polled per cycle can be expressed as

$$\tilde{N}_{circ} = N_{circ} + F_{cr} \cdot N_{ring}$$

Such situations arise quite often in agriculture, for example, when grazing cows in a pasture.

The total energy, taking into account the transition from a larger ring to a small ring of width σ with a speed of movement v [m/s] during t and a probability of transition F_{cr}:

$$\bar{e}_F = \frac{4\pi^3 P_r}{C_t r C_r c^2} \left(\left(\delta A^3 - \sigma(\sigma + 2r)(A^2 + 4r^2) \right) \cdot (1 - F_{rc}) + 4r^2(r + \sigma)^2 \right) f^2 \nu \tau \quad (16)$$

where $A = \sigma + 2r$, $\sigma = vt$.

Using the above expressions, we performed a numerical calculation and analyzed the influence of the parameters of an ubiquitous sensor network on the power consumption of the radio signal at the transmitting antenna of the sensor device. The calculations were carried out with the following initial data: speed of light $c = 3 \cdot 10^8$ m/s, density $\nu = 0.33\ \frac{1}{m^2}$, gain $C_{tr} = 1$, $C_r = 1$, radio frequency $f = 13.56 \cdot 10^6$ Hz, speed of movement of sensor devices $v = 1$ m / s, transference time $t = 1$ s, large ring width $\delta = 50$ m, small circle radius $r = 10..50$ m, data block transmission time $\tau = 1 \cdot 10^{-3}$ s. The receiver sensitivity limit is -110 dBm, which corresponds to $P_r = 10^{-14}$ W.

The effect of the speed of movement of sensor devices along the sensor field on energy consumption is shown in the figure 3.

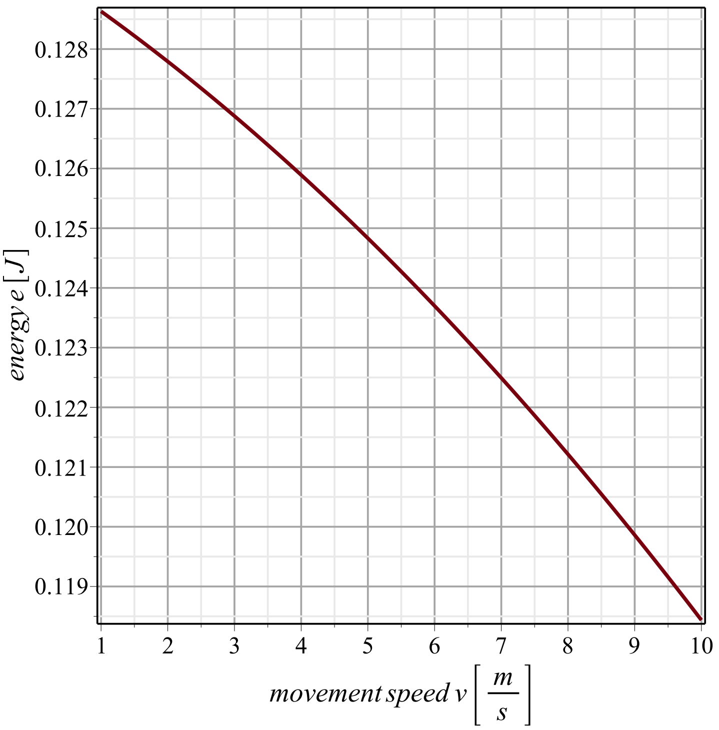

Fig. 3: Energy dependence on sensor speed.

The figure 4 shows the difference in energy consumption in two cases: without taking into account the movements of the sensor devices (Fig. 1(A)), and the case when the discipline with relative priorities is used (Fig. 1(B)).

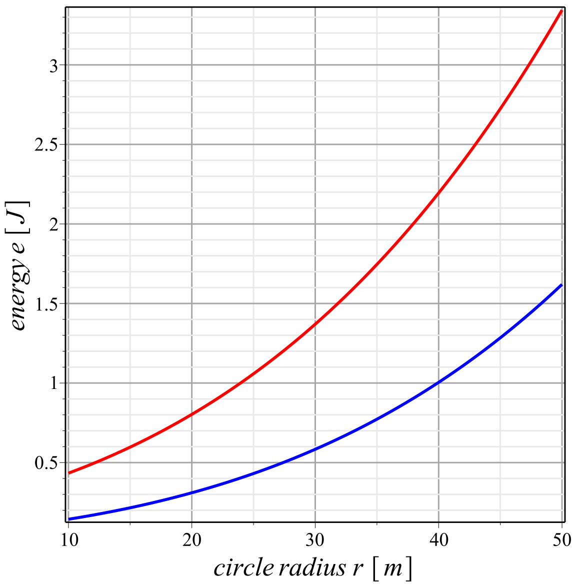

Fig. 4: Top score for energy consumption.

Energy consumption depending on changes in the radius of the small inner circle and the probability of transition is presented in Fig. 5.

Energy consumption depending on the radius of the inner circle at different values of the probability of transition of the sensor devices from the large circle closer to the base station (case C in Fig. 1) is shown in Fig. 6.

The resulting model made it possible to estimate energy consumption when using priority service discipline.

4 Conclusion

In this work we obtained probability distribution function for random power values of the radiating antenna of the sensor device, which provides a stable transmission of information. An assessment of the influence of spatial parameters of an ubiquitous sensor network on its total energy consumption is proposed. Under certain laws of motion of these sensor devices in the sensor space, the proposed model will significantly reduce the energy consumption necessary for the interaction of mobile sensor devices.

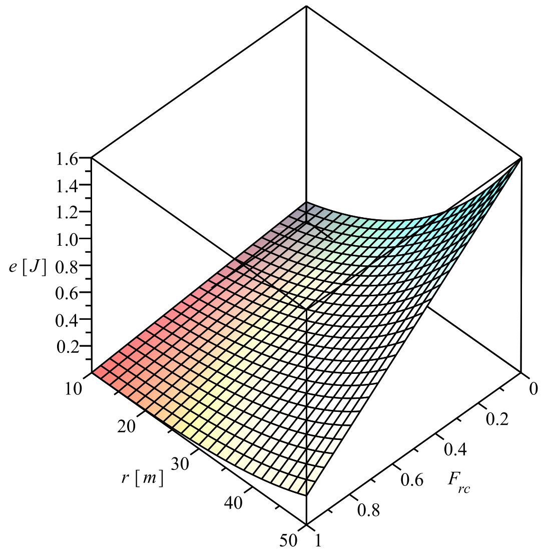

Fig. 5: Dependence of energy consumption on radius of small circle and probability of movement of sensor devices.

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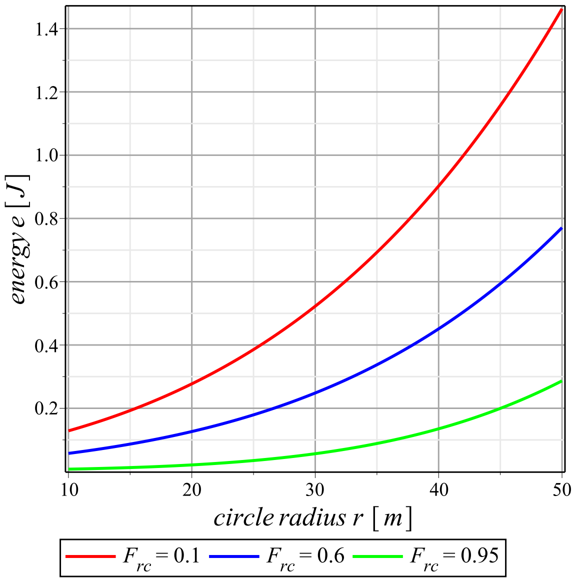

Fig. 6: Dependence of energy consumption on radius of small circle for different values of probability of movement of sensor devices.

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