Two-phase Model of Information Interaction in a Heterogeneous Internet of Things Network at the Last Mile

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Abstract

A protocol for information interaction of IoT sensors on the last mile is proposed. The developed access protocol takes into account the peculiarities of cyber-physical systems: heterogeneity of supported applications, superdensity of networks, the need to save resources of network components (frequency resource of the channel, energy intensity of smart things). A scenario of access to the resources of the over-the-air access network at the last mile is described, using a two-phase service model for heterogeneous data streams from smart things. The first phase: managing the volume of traffic going to global infocommunication resources. The second phase is the transmission of blocks of data in accordance with a controlled time-synchronous multiple access method. A mathematical model is proposed that makes it possible to assess the quality of transmission in the considered Internet of things network. Expressions are obtained for calculating the probabilistic-temporal characteristics of the transmission process of various types of data: the average time and the probability of timely delivery of data blocks generated by smart things, and the information rate of real time. A numerical calculation and analysis of the influence of traffic volume control procedures and multiple access parameters on the probabilistic-temporal characteristics of the transmission process on the last mile networks is carried out.

Keywords

Internet of things, smart things, last mile, managed multiple access, two-phase service model, probabilistic time characteristics

1. Introduction

The infrastructure base for IoT applications in many subject areas is over-the-air sensor networks. Their use, when creating cyber-physical systems [1, 2] to support any economic activity, requires taking into account the following aspects:

- autonomy of power supply of smart things (ST) and, accordingly, the limitedness of their resources (primarily energy resources that determine the life of ST) and the need to save them [3, 4, 5];

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- a large number of ST and the formation of so-called superdense networks [6, 7], for which the rational distribution of limited resources (available transmission channels) between data sources becomes an urgent task;
- the number of ST providing coverage of any space with an information grid and collecting the same type of information about their environment is initially redundant, sensors collect and transmit duplicate information. Therefore, a partial loss of information from a group of sensors of the same type monitoring one space will not significantly affect the adequacy of the assessment of the situation in this space;
- a variety of supported applications of the Internet of Things, which may have different requirements for the quality [8] and reliability of data transmission [9, 10] required for their functioning. For example, in medicine: readings from sensors measuring the patient's body temperature can be transmitted much less often than readings from sensors measuring his pulse rate.

The combination of the above features led to an increase in the load on the last mile networks. The shortage of the available frequency resource of the air network leads to situations of overload and the impossibility of full service of all ST. To minimize the negative impact of overloads on the functioning of the infrastructure of the cyber-physical system, supported applications of the Internet of Things, it is necessary:

- firstly, when organizing data collection at the last mile, provide mechanisms for limiting (or discarding) part of the traffic coming from smart things [11];
- secondly, take into account the heterogeneous nature of the supported IoT applications (for example, the sensitivity of applications to transmission delays [12]).

2. Physical network structure and multiple access protocol

An urgent task is to develop new protocols for access to global information and communication resources that would take into account all the listed features of modern networks and would allow adaptively managing the volume of incoming traffic [13] to eliminate network congestion on the last mile, as well as provide the required transmission quality for various types of Internet applications things [12].

The base station (BS) provides multiple access of smart things to global information and communication resources. The zone of its action covers the space on which smart things of I types are located. In fig. 1 there are three types of such things ($I = 3, i = 1, 2, ..., I,$). The base station uses a fixed number (L) of the same type of radio channels. Each such radio channel, in turn, represents a common resource for a number of smart things. To share the channel resource, multiple access algorithms are used. It is assumed that smart things of each type support the operation of applications of the same kind. Each of the I of such applications imposes specific requirements for the transmission quality, which are described by the function of distributing the delivery time of data blocks from smart things to the resources of the global network. Within the framework of this study, we will assume that for each type of smart things, an exponential time of the admissible delay of a data block with an average value $T_i[s]$, $i = 1, 2, ..., I$ is set.

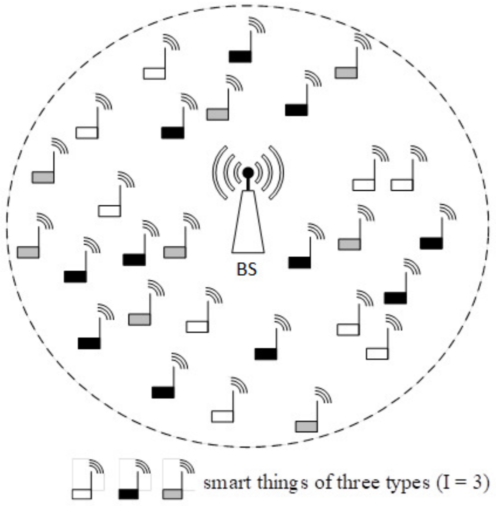


Figure 1: The physical structure of the investigated last mile ether network.

One transmitted message from a smart thing of all types is one data block of length k [bits], so the time windows for the transmission of these blocks have the same duration. This allows using controlled synchronous-time access to organize M time windows in each of the L radio channels. Thus, the total number of time windows available for smart things is:

$$W = M \cdot L \tag{1}$$

When administering the operation of such a network, it is possible in different ways to distribute the bandwidth of radio channels between smart things of different types.

When administering the operation of such a network, it is possible in different ways to distribute the bandwidth of radio channels between smart things of different types. Fig. 2 (a) shows an example (for $I = 3$), when one fixed radio channel is assigned to a smart thing of each type. In Fig. 2 (b), the bandwidth of each radio channel is equally distributed among smart things of all types (for $I = 3$).

In this study, it is proposed to use a more general, regulated multiple access, in accordance with which any smart thing has access to any radio channel, and the bandwidth of each radio channel is divided among smart things in unequal proportions, which makes it possible to provide different quality of service for traffic different types. Smart things of each type are allocated a different number of time windows in each cycle.

M_i – the number of time windows that are available to smart things of the i-th type ($i = 1, 2, ..., I$).

If a smart thing of one type admits a greater time delay in the transmission of a data block than a smart thing of another type, then in the cycle they are allocated a smaller number of time windows. The fixing of time windows for things of different types should be carried out in such a way that all time windows are used. Figure 3 below shows an example of the structure of a transmission cycle when using variable synchronous-time multiple access for the case

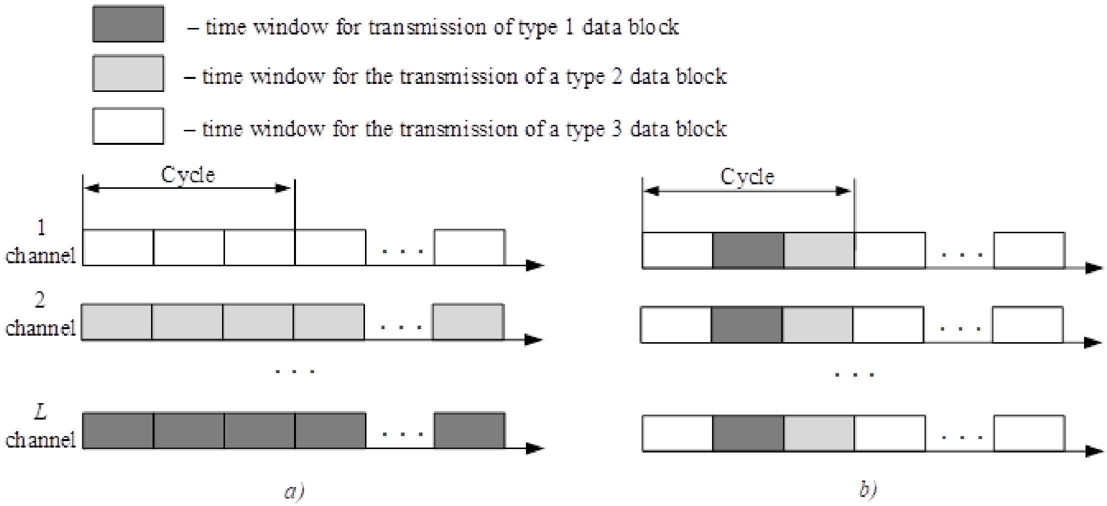


Figure 2: Distribution of radio bandwidth between smart things of different types.

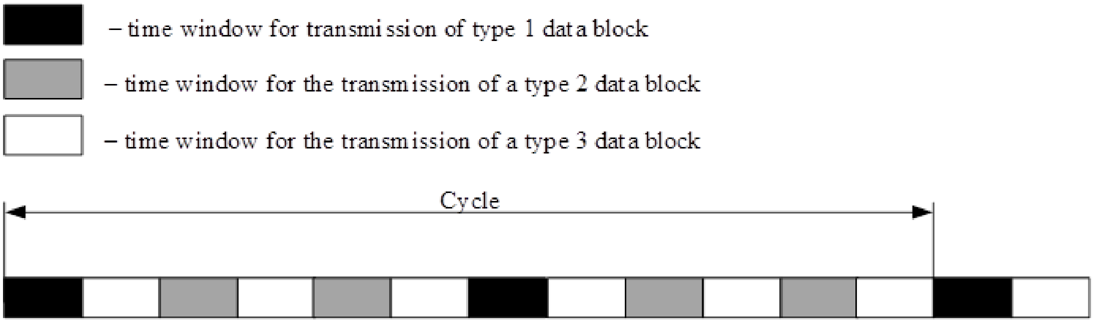


Figure 3: Example of a transmission frame structure when using variable synchronous time multiple access.

$M = 12$, $I = 3$, $M_1 = 2$, $M_2 = 4$, $M_3 = 6$. This approach allows flexible sharing of the common resource of radio channels in the last mile network.

To reduce the load on the channel resources of the last mile network, it is proposed dynamically, depending on the volume of traffic coming from the ST, to discard that part of it for which there are not enough free channels of the corresponding type. In this case, the transmission of data blocks arriving from the ST is carried out in 2 phases:

The 1-st phase – traffic volume limitation. Lossy service mode is assumed, i.e. in the case when a request is received for the transmission of a data block from an ST, and there are no free channels of the corresponding type, then the request is discarded.

In the 2nd phase, there are parameters that the limiting mechanism of the 1st phase can influence and there are parameters that it cannot influence. The independent ones include: the duration of the time window, the duration of the cycle, the service time for the thing of the i-th type (the time of transmission of one data block). The number of dependent include the

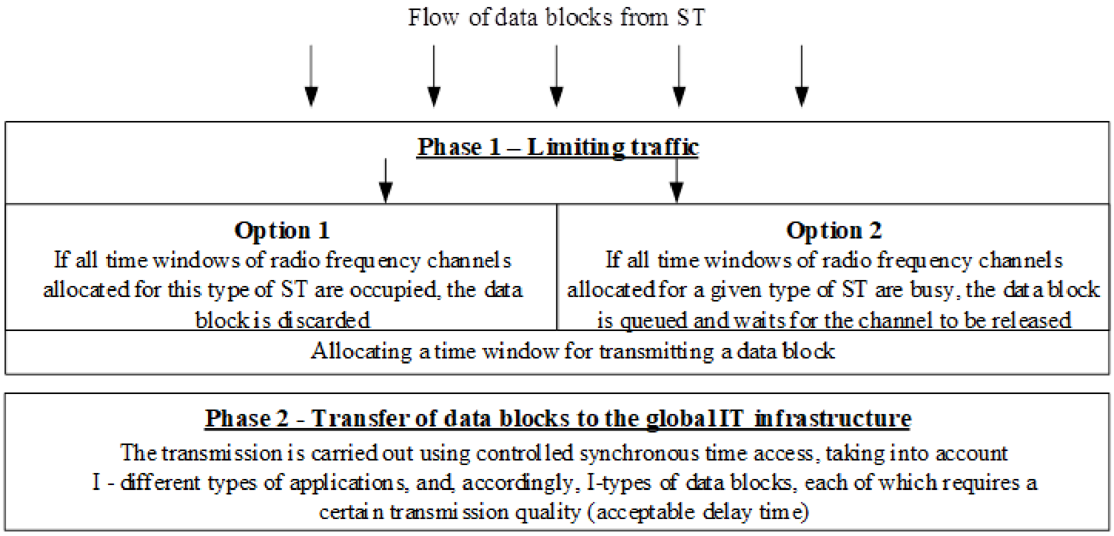


Figure 4: Last mile access scenario.

probability of packet loss due to late delivery of the data block, the average transmission delay time, and channel loading.

In this article, we will consider the case when the limiting mechanism takes into account only the service time for the i-th item (the time of transmission of one data block).

The 2-nd phase – transmission of data blocks in accordance with the regulated synchronous-time method of multiple access, which provides for the regulation of ST access to the transmission channel: the stricter the requirements for the permissible delay time of the data block over the network, imposed by the Internet of Things application, the more often the ST supporting the operation of this application gets the right to transmit and the shorter the interval of a single transmission of the data block for the ST of this type.

3. Mathematical model

When developing a mathematical model, we will assume the following:

I – the number of ST types, ($i = 1, 2, ..., I$). ST with a lower number require a lower data transfer rate, and the lowest speed is required for STs of the 1st type - and, accordingly, the value of the average permissible data aging time T_i [s] is maximum.

M – total number of windows in one transmission channel:

$$M = M_1 + M_2 + M_3 \tag{2}$$

Items of the same type use the resources allocated to them in the first and second phases. The blocks of data they generate form a Poisson stream.

V – the speed of data transmission over the radio channel in the second phase [bit/s]. We assume that the speeds of all radio channels are the same.

The entire time of using one channel is divided into cycles, which, in turn, are divided into time windows. Window duration for the transmission of one data block $T_{ok} = \frac{k}{V}$.

The window duration is sufficient for the transmission of a data block and is the same for all types of ST.

τ_i – average service time of a data block for an i-th type ST (time of transmission of one data block received from items of i-th type):

$$\tau_i = \frac{k \cdot M}{V \cdot M_i}, \quad i = 1, 2, ..., I \tag{3}$$

N_i the number of time windows in the second phase that are available for the i-type ST:

$$N_i = M \cdot L, \quad i = 1, 2, ..., I \tag{4}$$

It is assumed that all RF channels are identical in their logical structure (see, for example, Fig. 3).

Λ–flow rate of incoming data blocks [block/s]. Λ_i–the rate of receipt of data blocks from the i-type HC ($i = 1, 2, ..., I$).

q_i– the proportion of data blocks of the i-th type in the total stream of data blocks Λ.

A_i–the intensity of the load created by the i-type ST:

$$A_i = \Lambda \cdot q_i \cdot \tau_i \tag{5}$$

1st phase

P_i–the probability of blocking a data block from an i-type ST in the first phase due to the absence of free time channels in the second phase. The probability P_i can be calculated using the first Erlang formula:

$$P_i = \frac{A_i^{N_i}}{N_i!} \left[\sum_{n=0}^{N_i} \frac{A_i^n}{n!} \right]^{-1}, \quad i = 1, 2, ..., I \tag{6}$$

2nd phase

λ_i– the intensity of the arrival of data blocks of the i-th type of ST to one arbitrary radio channel of the second phase. It is assumed that the data blocks arriving at the second phase are evenly distributed between all radio frequency channels and therefore the intensity of their arrival in the multiple access system of one radio channel is determined as follows:

$$\lambda_i = \frac{\Lambda_i (1 - P_i)}{L} \tag{7}$$

$B_i(s)$ –Laplace-Stieltjes transform (PST) of the transmission time of a data block of the i-type ST ($i = 1, 2, ..., I$):

$$B_i(s) = e^{\frac{-s \cdot M \cdot T_{ok}}{M_i}} \tag{8}$$

$W_i(s)$–Laplace-Stieltjes transform waiting time for the start of data block transmission from the i-type ST ($i = 1, 2, ..., I$):

$$W_i(s) = \frac{s \cdot (1-\rho_i)}{s - \lambda_i + \lambda_i \cdot B_i(s)} \tag{9}$$

ρ_i–loading the transmission medium with data blocks of the i-th type:

$$\rho_i = \lambda_i \cdot \tau_i \tag{10}$$

Ergodicity condition for the second phase: $0 < \rho_i < 1$, $i = 1, 2, ..., I$.

Probability-time characteristics of the process of servicing requests.

Average delay time of transmission of data blocks coming from i-type ST. As a result of differentiation, we obtain expressions for calculating $\bar{t}_i$:

$$\bar{t}_i = \frac{\tau_i \cdot (\rho_i - 2)}{2 \cdot (\rho_i - 1)} \tag{11}$$

Probability of timely delivery of data blocks from i type ST. As a result of differentiation, we obtain expressions for calculating Q_i:

$$Q_i = \frac{(1-\rho_i) \cdot e^{\frac{\tau_i}{T_i}}}{T_i \cdot (\frac{1}{T_i} - \lambda_i + \lambda_i \cdot e^{\frac{\tau_i}{T_i}})} \tag{12}$$

where T_i– average admissible delay time of data block transmission from i-type ST ($i = 1, 2, ..., I$).

The information speed of the real-time network for each type of ST shows the amount of information of the corresponding type actually transmitted in time (in bits) per unit of time (s). Losses in the simulated system can occur on: 1st phase. Losses are characterized by P_i – the probability of blocking a data block from an i-type ST in the first phase due to the absence of free time channels in the second phase; 2 phase. Losses are characterized by Q_i – the probability of timely delivery of data blocks coming from the i-th ST.

Accordingly, the expression for calculating the real-time information rate for the i-th type ST will be:

$$R_{PB_i} = \Lambda_i \cdot k \cdot P_i \cdot Q_i \tag{13}$$

4. Results of numerical experiments

Numerical experiments were carried out - the calculation of the probabilistic-temporal characteristics of the transmission of data blocks from three types of ST (i.e., $I = 3$) in the wireless sensor network of the Internet of things.

Initial data for calculations: $Z = 2$, $M_1 = 1$, $M_2 = 2$, $M_3 = 3$, $k = 1024$ [bit], $V = 210000$ [bit/s], $q_1 = \dfrac{1}{15}$, $q_2 = \dfrac{1}{3}$, $q_3 = \dfrac{3}{5}$, $T_1 = 0.1$ [s], $T_2 = 0.3$ [s], $T_3 = 0.6$ [s].

The Fig. 5–7 are graphs illustrating the results of numerical experiments. The influence of the intensity of the arrival of data blocks on transmission, as well as the introduction of a restriction on the volume of incoming traffic (i.e., the first phase of service), on the probabilistic-temporal characteristics of the process of transmitting data blocks from three types of ST in the last mile access network was studied.

Figure 5 (a) is a graph of the dependence of the probabilities of blocking data blocks in the first phase on the intensity of their receipt from hydrocarbons of all types. It shows that for different types of things, the blocking will be different depending on the ratio of the intensity of the load and the number of time channels allocated for things of the corresponding type in the second phase.

Figure 5 (b) is a graph of the dependence of the intensity of the arrival of data blocks in the second phase on the intensity of the arrival of data blocks in the first phase. This graph illustrates the process of rejection in the first phase of a part of blocks arriving from the ST – the part that will not receive quality service in the second phase. For example, for blocks of the second type, taking into account the presence of two frequency channels (L = 2) and the share in the total flow of blocks at an intensity $\Lambda = 250$ block/s $q_2 = 1/3$, 95% of the traffic will be passed to the second phase.

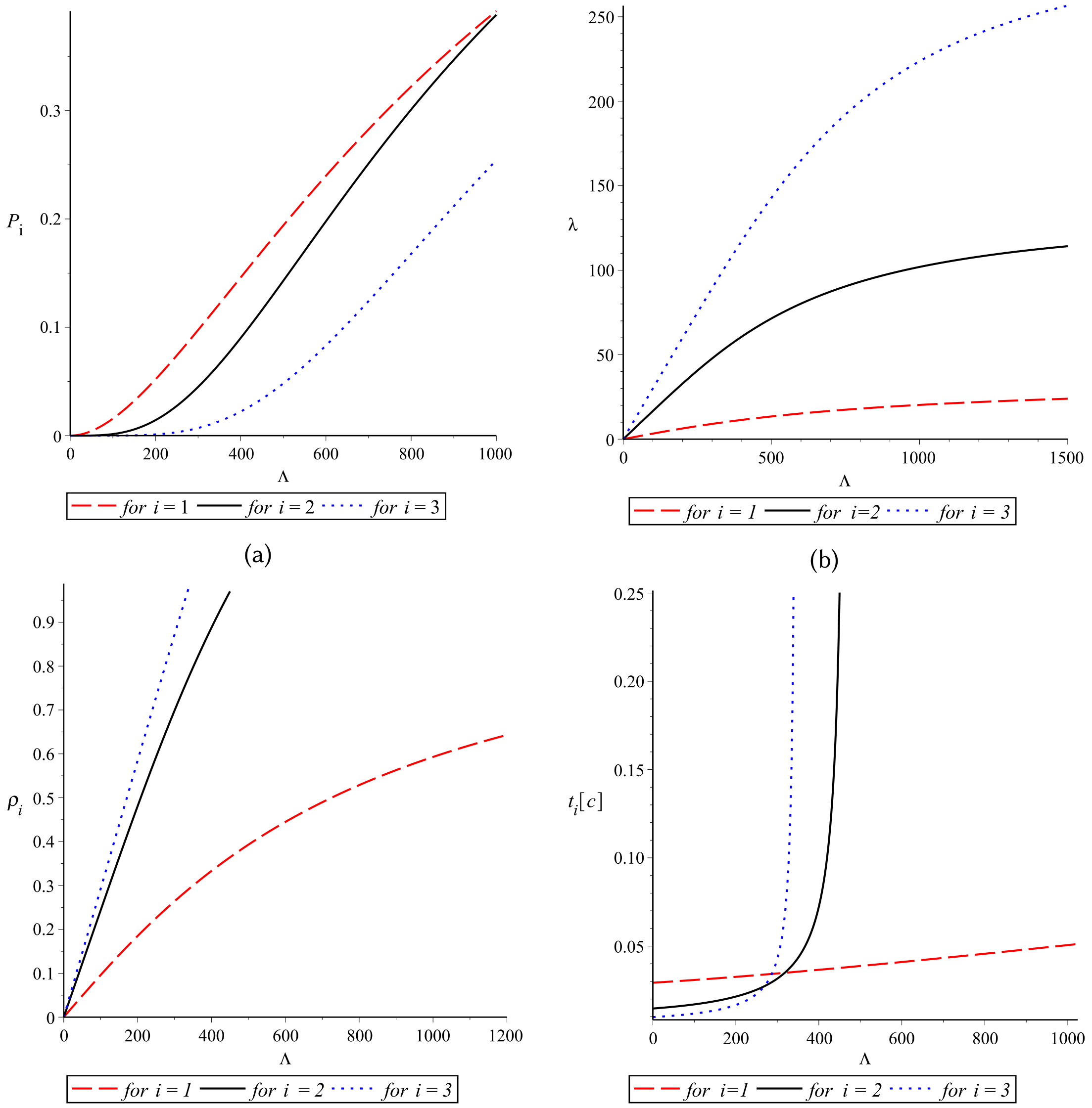
Figure 5 (c) is a graph of the dependence of the load of the temporary channels allocated for the transmission of data blocks of each type in the second phase of service on the intensity of the arrival of the data blocks. The selected controlled access method allows serving blocks of one type even in a situation of loss of ergodicity in temporary channels of other types. This circumstance is illustrated in Fig. 5 (d), Fig. 6 (a) and Fig. 6 (b), which show the graphs of the dependence: the average delay time – Fig. 5 (d), probabilities of timely delivery - Fig. 6 (a) and information speed of the real-time network – Fig. 6 (b) data blocks on the intensity of their receipt for transmission.

In Fig. 6 (c), Fig. 6 (d) and Fig. 7 shows the same characteristics only for the second type of ST: $t_2(\Lambda)$ – in Fig. 6 (c), $Q_2(\Lambda)$ – in Fig. 6 (d) and $R_{PB2}(\Lambda)$ – in Fig. 7 for two cases – the presence and absence of the first phase (i.e., the presence and absence of traffic volume limitation). As can be seen from the graphs of dependencies, the introduction of the limitation procedure in the first phase allows increasing the stability of the network as the intensity of the incoming data blocks increases.

5. Conclusion

The article proposes a protocol of regulated multiple access to radio resources of the Internet of Things network at the last mile, which takes into account the peculiarities of cyber-physical systems: heterogeneity of supported applications, superdensity of networks, the need to save resources of network components.

A scenario of access to network resources at the last mile is described, which uses a two-phase service model for heterogeneous data streams coming from different types of ST. In the first phase, an adaptive limitation of the volume of traffic received for service is provided. There are two options for organizing regulation in the first phase: service with obvious losses and service with waiting. The article discusses in more detail the first version of the mode - with obvious losses of data blocks arriving for transmission, in the absence of free channels in the network. In the second phase of the service, data blocks are transmitted in accordance with a controlled time-synchronous multiple access method..

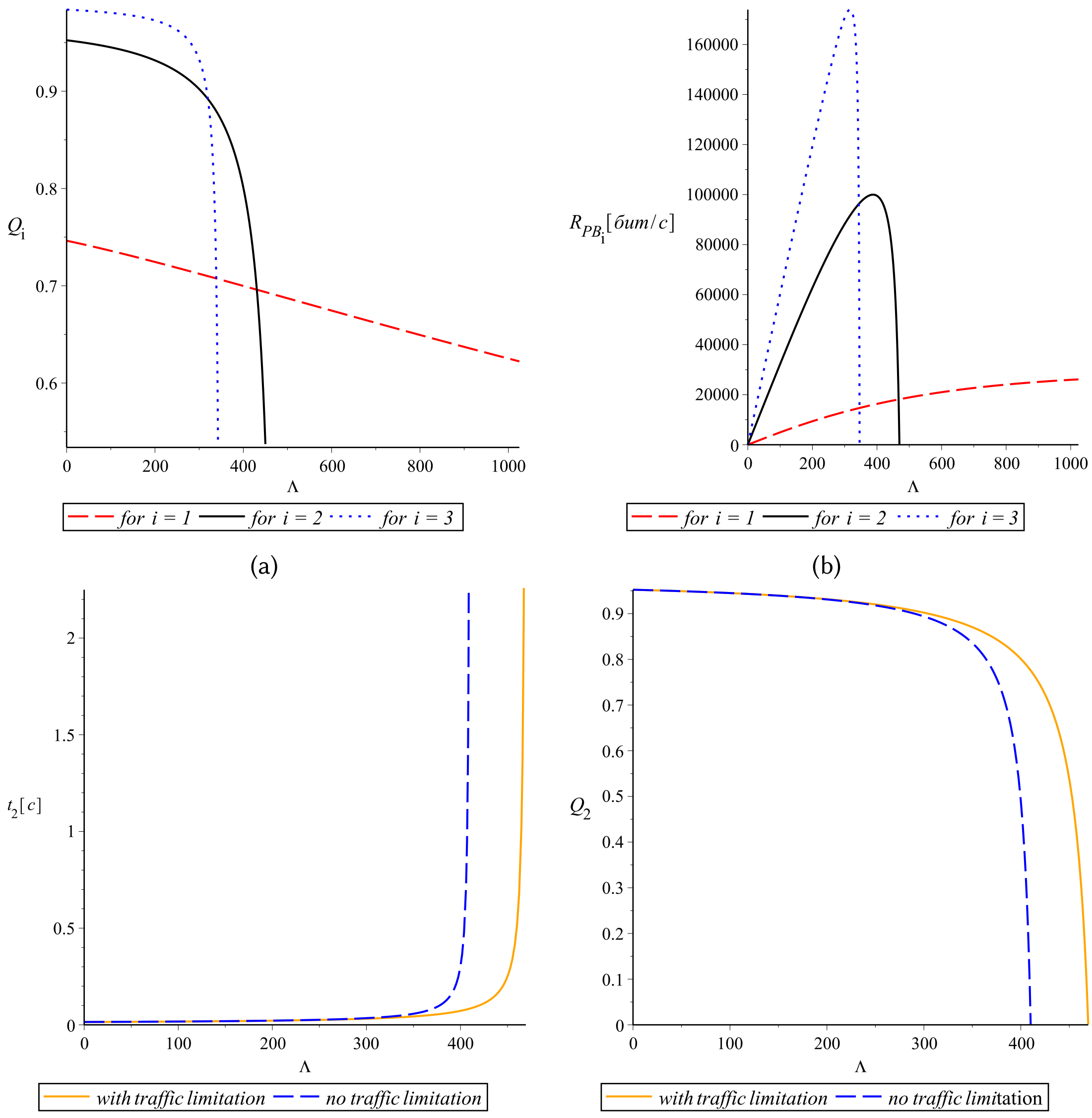


(a) (b)

(c) (d)

Figure 5: Dependence of the: (a) probability of blocking data blocks in the first phase on the intensity of their arrival from hydrocarbons of all types; (b) intensity of the arrival of data blocks in the second phase on the intensity of the arrival of data blocks in the first phase; (c) loading of temporary channels allocated for the transmission of data blocks of each type in the second phase of service on the intensity of the arrival of data blocks; (d) average delay time of data blocks on the intensity of their arrival for transmission.

A queuing model has been obtained that describes the process of data transmission from different types of ST in the form of a two-phase QS, which makes it possible to estimate the probabilistic-temporal characteristics of the data transmission process of things of different types.



(a) (b)

(c) (d)

Figure 6: Dependence of the: (a) probability of timely delivery of data blocks on the intensity of their arrival for transmission; (b) information speed of the real-time network of data blocks on the intensity of their receipt for transmission; (c) average delay time of data blocks on the intensity of their arrival for transmission, for the second type of ST; (d) probability of timely delivery of data blocks on the intensity of their receipt for transmission, for the second type of ST.

Numerical experiments were carried out to assess the effect of the traffic volume limitation procedure in the first phase of service on the transmission quality in the last mile access network - on the probabilistic-temporal characteristics of the process of transmitting data blocks from three types of ST, which illustrated the efficiency of using the proposed protocol and the controlled multiple access scenario. The introduction of a procedure for filtering out a part of

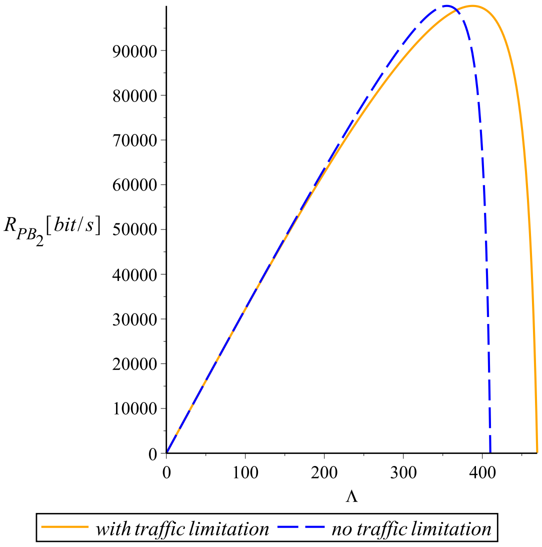


Figure 7: Dependence of the information speed of the real-time network of data blocks on the intensity of their receipt for transmission, for the second type of ST.

the traffic in the first phase makes it possible to increase the range of operating intensity of data blocks arriving for transmission.

References

[1] Kupriyanovskiy, V. P., Namiot, D. Ye., Sinyagov, S. A. Kiber-fizicheskiye sistemy kak osnova tsifrovoy ekonomiki [Cyber-physical systems as a base for digital economy] // International Journal of Open Information Technologies, vol. 4, no. 2. pp. 18-25, (2016)

[2] Astakhova, T. N., Kolbanev, M. O., Romanova, A. A., Shamin, A. A. Model of digital agriculture // International Journal of Open Information Technologies, Vol. 7. no. 12, (2019)

[3] Roslyakov, A. V. Otsenka energopotrebleniya budushchikh setey [Measuring of energy consumption of future networks] // Elektrosvyaz'.**8**. pp. 43–50, (2016)

[4] Astakhova T., Kirilova D., Shamin A., Kolbanev M. Research on the energy characteristics of routing in wireless sensor net-works // CEUR Workshop Proceedings. 11. MICSECS 2019 – Proceedings of the 11th Majorov International Conference on Software Engineering and Computer Systems, (2020).

[5] Astakhova T., Kirilova D., Kolbanev M., Maslov N., Shamin A. Criterion for choosing the optimal message transmission route in wireless sensor networks // Telekommunikatsii [Telecommunications], no.7, pp. 6–12, (2020)(In Russian).

[6] Zakharov, M. V., Kirichek, R. V. Metody postroyeniya sverkhplotnoy seti e-health s ispol zovaniyem granichnykh vychisleniy [Methods for building a super-dense e-health network using edge computing]// SPbNTORS: trudy yezhegodnoy NTK. SPbGETU «LETI». **1**(75). pp. 145–147, (2020)

[7] Borodin, A. S., Kucheryavyy, A. Ye., Paramonov, A. I. Osobennosti ispol zovaniya D2D-

tekhnologiy v zavisimosti ot plotnosti polzovateley i ustroystv [Features of using D2D communication at various subscriber densities]// Elektrosvyaz. **10** pp. 40-45, (2018)

[8] Kucheryavyy, A. Ye., Makolkina, M. A., Kirichek, R. V. Taktilnyy Internet. Seti svyazi so sverkhmalymi zaderzhkami [Tactile internet. Ultra-low latency networks] // Elektrosvyaz. 1. pp. 44-46, (2016)

[9] Bogatyrev, V.A. Exchange of duplicated computing complexes in fault-tolerant systems // Automatic Control and Computer Sciences, Vol. 45, No. 5, pp. 268–276, (2011)

[10] Bogatyrev, V.A. Fault Tolerance of Clusters Configurations with Direct Connection of Storage Devices // Automatic Control and Computer Sciences 2011, Vol. 45, No. 6, pp. 330-337, (2011)

[11] Verzun, N., Kolbanev, M., Shamin, A. The Architecture of the Access Protocols of the Global Infocommunication Resources Computers 2020, 9, 49; https://doi.org/10.3390/computers9020049

[12] Verzun, N. A., Kolbanov, M. O., Omelyan, A. V. Reguliruyemyy mnozhestvennyy dostup v besprovodnoy seti umnykh veshchey [Controlled multiple access in wireless network of smart things]// Omskiy nauch. vestn. Ser. Informatika, vychislitel'naya tekhnika i upravleniye. **4**(148). pp. 147–151, (2016)

[13] Bogatyrev, V.A., Protocols for dynamic distribution of requests through a bus with variable logic ring for reception authority transfer /Automatic Control and Computer Sciences v33(1). pp. 57-63, (1999)