MODEL OF PROCESSES FOR JOINT MAINTENANCE OF REAL-TIME MULTISERVICE TRAFFIC AND ELASTIC DATA TRAFFIC IN A NETWORK OF LOW-POWER MOBILE SUBSCRIBER TERMINALS BASED ON HIGH-THROUGHPUT SATELLITES

Alexander A. Maslov,
Moscow Institute of Physics and Technology (MIPT), Moscow, Russia, ***maslov.aa@mipt.ru***

Gennady V. Sebekin,
Moscow Institute of Physics and Technology (MIPT), Moscow, Russia, ***sebekin.gv@mipt.ru***

Sergey N. Stepanov,
Moscow Technical University of Communications and Informatics; Kotel'nikov institute of radio engineering and electronics of RAS, Moscow, Russia, ***s.n.stepanov@mtuci.ru***

Alexey O. Shchurkov,
Moscow Institute of Physics and Technology (MIPT), Moscow, Russia, ***shchurkov.ao@mipt.ru***

Alexsander P. Vasilyev,
Moscow Technical University of Communications and Informatics, Moscow, Russia

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To implement the functions of planning and distributing channel resources in networks of low-power mobile subscriber terminals based on high-throughput satellites in geostationary and highly elliptical orbits, it is necessary to develop models for the joint maintenance of real-time multiservice traffic and elastic data traffic. The models should take into account the uneven placement of terminals in local areas, their limited number, the possibility of simultaneous servicing by each terminal of requests for the transmission of two types of traffic, one of which is elastic data traffic, the other real-time traffic, with a limit on the speed of information transfer by the terminal. The purpose of the work is to solve the modeling problem taking into account the listed factors. Model based on multidimensional stepwise Markov processes is constructed. A list of tasks that can be solved using the model is defined, including both the tasks of determining the minimum required network resource to meet the specified quality requirements, and the tasks of finding preferred resource distributions between local areas according to the criterion of minimizing the average service time for data transfer requests. Numerical examples of solving each task are presented. The developed model can be used in the construction of control systems for information transmission networks based on high-throughput satellites.

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1 Introduction

Currently, the Russian Federation is actively working on the development of a satellite constellation, including, inter alia, high-throughput satellites (HTS) in highly elliptical and geostationary orbits, and the creation on this basis of broadband subscriber access systems to public terrestrial networks, in particular, the Internet [1, 2, 23]. At the same time, mobile satellite communication services, especially broadband access for vehicles, are coming to the fore [3]. The possibilities of creating terminals for such systems are confirmed, for example, in [4]. The article considers a broadband satellite network with the topology "star" based on HTS, where low-power subscriber terminals (ST) installed on vehicles in local service areas (LA) of the spacecraft's on-board antenna beams provide drivers with access to services of communication and data transmission via a central earth station (CS) connected to terrestrial telecommunications networks (Fig. 1).

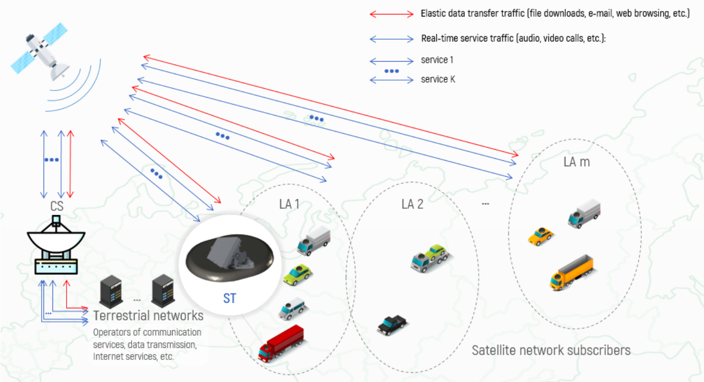

Fig. 1. Network structure

The provision of services is carried out according to requests processed by the CS management system, and depending on the characteristics of the services requires either real-time traffic transmission (for example, for voice or video calling services), or allows delays and changes in the transfer speed (file downloads, e-mail, etc.). Accordingly, traffic on the network can be conditionally split into real-time traffic and elastic traffic. In addition to the uneven distribution of a given number of ST in a certain set of LA, the analyzed network has the following features:

1) Due to the low power, the ST cannot occupy the entire frequency band of the beam, and, accordingly, the maximum transmission speed is limited.

2) ST are personal. Therefore, it can be assumed that drivers use no more than one real-time service at any given time, although data can be exchanged simultaneously (for example, you can hold a telephone conversation and download files or browse web pages, etc.).

The traffic generated when receiving services is serviced by providing the necessary channel resource, which, as a rule, is expressed as an integer number of information transfer speed units (bits/s) [5]. In this case, the speed unit is usually chosen as the largest common divisor of the set of speeds required for transmitting different types of traffic. The quality of network operation is often assessed by such indicators as the proportion of requests for the transmission of traffic of each type, lost due to the lack of a free channel resource, as well as the average service time of the request for data transmission [5].

To solve the tasks of planning and distributing a channel resource in a network of low-power ST based on HTS, it is necessary to develop mathematical models of network functioning processes that allow evaluating the values of quality indicators depending on the volume of resources provided, taking into account the set and characteristics of the services, the number and intensity of ST work, their placement on the LA, accepted procedures for the provision of a resource. The assessment should be carried out both for an individual LA and for the network as a whole. The purpose of this article is to develop these models that take into account the listed features of the ST network.

A large number of papers have been devoted to modeling the processes of servicing multiservice traffic (for example, [6-21]). These issues are considered in relation to various telecommunication networks and applications (to access nodes of mobile communication networks (for example, [6, 14, 15, 16]), The Internet of Things (for example, [10, 11, 14, 17]), surveillance systems (for example, [6, 9]), cloud computer systems (for example, [13]), satellite communication systems (for example, [19-21]). The general approach (([5, 13-21]) involves the assumption of the Poisson nature of the input streams and the exponential distribution of service times and volumes of transferred files, which allows us to build models based on multidimensional stepwise Markov processes that take into account the main specifics of the analyzed systems.

The irreversibility of these processes makes it difficult to obtain analytical results. Estimates of quality indicators are based on the numerical solution of systems of equilibrium equations (SEE). Direct use of the results of the work [5-20] is impossible, because they do not take into account the factors associated with the placement of ST in a set of LA, as well as the admissibility of simultaneous transmission by one ST at a limited speed of two information flows, one of which relates to real-time traffic, the second to elastic traffic. The maintenance of streams generated from several LA is considered in [21], however, the noted features of the ST operation are also not taken into account there. In order to achieve this goal, section 2 builds a mathematical model for the joint maintenance of multiservice traffic on the network. Section 3 is devoted to the characterization of tasks that can be solved using the developed model. Section 4 provides numerical examples of solving such tasks using the model.

2 Mathematical model

Let's first consider a fragment of a network that includes N homogeneous ST of one LA (Fig. 2). Let the resource allocated to the area be v units. Each ST can simultaneously serve traffic from one of the K real-time services and elastic data traffic.

Note that the case when a subscriber can use no more than one service at a time belongs to the Engset type models, the state of which is determined by the vector of the number of subscribers receiving each service [5]. In the network under consideration, an ST can receive up to two services at once, i.e. this approach is not applicable. The same service characteristics are provided by the ST using the same services at the current time. To account for this circumstance, the state of the ST is denoted by a pair (k,q), where k is the number of the real–time service from 1 to K or 0, q is one or zero, depending on whether data traffic is currently being serviced or not. Obviously, the total number of ST states is $2(K+1)$. The graph of transitions between states is shown in Figure 3.

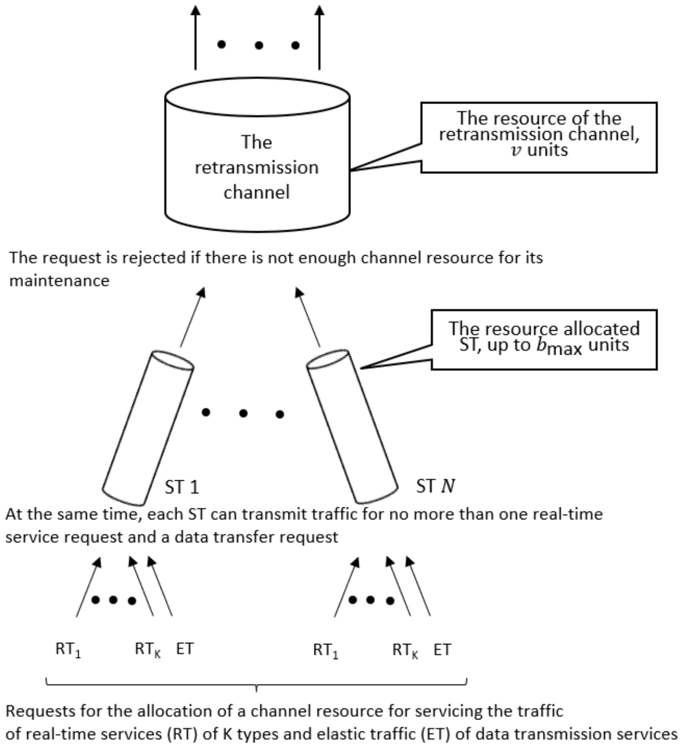

Fig. 2. Features of joint maintenance of real-time and elastic traffic in a separate LA

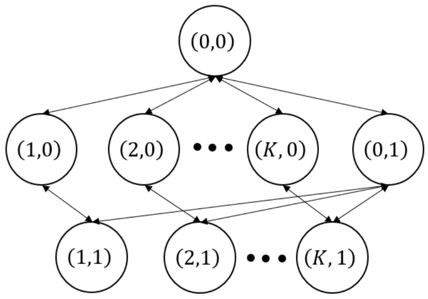

Fig. 3. Graph of transitions between ST states

Let the resource volumes required for servicing requests be given by the vector $(b_1, b_2, \dots, b_K, b_e)$, where b_k (k =1, 2, …, K) are the resource values for requests for real-time traffic transmission and b_e is the minimum resource for servicing data transfer requests. In this case, the maximum resource for a data transfer request is $b_{\max}$ and is determined by the maximum transfer speed of ST. Let's introduce a vector $\boldsymbol{b}=\left(0, b_1, \dots, b_K, b_e, (b_1+b_e), \dots, (b_K+b_e)\right)$ consisting of *2(K+1)* components, the first (K+1) components of which correspond to the states ST from (0,0) to (K,0), and the second (K+1) components of the ST states from (0,1) to (K,1). We also denote by $n_{(k,q)}$ the number of ST that are currently in the state (k,q), and by $\boldsymbol{n}=\left(n_{(0,0)}, \dots, n_{(K,0)}, n_{(0,1)}, \dots, n_{(K,1)}\right)$the vector of the amounts of ST in the considered LA, which are in the corresponding states. The sum of the components $\boldsymbol{n}$ is equal to the number of ST in LA N. Obviously, the minimum resource required to service all ST in the area in the current state is $l=\boldsymbol{n}\boldsymbol{b}^{\mathrm{T}}$, i.e., if the total resource of the LA is v, then incoming requests can be allocated a resource from the remaining part of v-l. In this case, the resource for transmitting data traffic can be increased to $b_{\max}$ if a particular ST is in the state (0,1), and to $(b_{\max}-b_k)$ if the ST is in the state (k,1), k=1,2,...,K. Note also that the number of requests for the transmission of real-time traffic of the k-th type served in the system is $\left(n_{(k,0)}+n_{(k,1)}\right)$, k=1,2,...,K, and the number of requests for data transmission is $\sum_{k=0}^{K} n_{(k,1)}$.

We will assume that the flows of requests for the transmission of real-time traffic and data are independent, the intervals between the moments of receipt of requests are subject to an exponential distribution. If the ST is not currently busy transmitting real-time traffic, then new requests are received with intensities β_k, $k=1,2,\dots,K$. In essence, this means that the interval until the moment of receipt of a new request for real-time traffic transmission has an exponential distribution with the parameter $\beta=\sum_{k=1}^{K}\beta_k$, and the probability that this will be a k-type request is ${}^{\beta_k}/_{\beta}$. Also, if the ST is not currently busy transmitting data traffic, then new requests arise with the intensity of β_e. The request service time is also subject to an exponential distribution with the parameters μ_k, $k=1,2,\dots,K$, and μ_e (μ_e corresponds to the transmission of data traffic at a minimum speed, i.e. when allocating a resource b_e.

The set of network states is written as:

$$S=\left\{\boldsymbol{n}:\boldsymbol{n}\boldsymbol{b}^{\mathrm{T}}\le v;\ n_{(k,q)}\ge 0, k=0,1,\dots,K, q=0,1;\ \sum_{k=0}^{K}\sum_{q=0}^{1} n_{(k,q)}=N\right\} \qquad (1)$$

The sets of network states for which incoming requests for the transmission of real-time traffic of type k are refused are defined as:

$$U_k=\left\{\boldsymbol{n}:\boldsymbol{n}\in S, \boldsymbol{n}\boldsymbol{b}^{\mathrm{T}}>v-b_k, \left(n_{(0,0)}+n_{(0,1)}\right)>0\right\}. \qquad (2)$$

In (2), the condition $\left(n_{(0,0)}+n_{(0,1)}\right)>0$ means that there are ST in the network capable of generating requests of type k. The set of network states for which incoming requests for data traffic are refused:

$$U_e=\left\{\boldsymbol{n}:\boldsymbol{n}\in S, \boldsymbol{n}\boldsymbol{b}^{\mathrm{T}}>v-b_e, \sum_{k=0}^{K} n_{(k,0)}>0\right\}. \qquad (3)$$

Similarly, in (3) the condition $\sum_{k=0}^{K} n_{(k,0)}>0$ means that there are ST in the network capable of generating requests for data traffic transmission.

Denote by $p(\boldsymbol{n})$, $\boldsymbol{n}\in S$, the probabilities of finding the network in state $\boldsymbol{n}$ in steady state. Let's assume that state $\boldsymbol{n}$, as a result of the occurrence of an event of receipt or completion of service of the request, can be reached from states $\boldsymbol{n_{in}}\in S_{in}(\boldsymbol{n})$ with transition intensities $a(\boldsymbol{n_{in}},\boldsymbol{n})$, and from state $\boldsymbol{n}$, as a result of the occurrence of an event of receipt or completion of service of the request, it is possible to get to states $\boldsymbol{n_{out}}\in S_{out}(\boldsymbol{n})$ with transition intensities $a(\boldsymbol{n},\boldsymbol{n_{out}})$. Then the probabilities $p(\boldsymbol{n})$ satisfy the SEE:

$$p(\boldsymbol{n})\sum_{\boldsymbol{n_{out}}\in S_{out}(\boldsymbol{n})} a(\boldsymbol{n},\boldsymbol{n_{out}})=\sum_{\boldsymbol{n_{in}}\in S_{in}(\boldsymbol{n})} p(\boldsymbol{n_{in}})a(\boldsymbol{n_{in}},\boldsymbol{n}), \boldsymbol{n}\in S \qquad (4)$$

To solve the SEE, as can be seen from (4), it is necessary to determine the sets $S_{in}(\boldsymbol{n})$, $S_{out}(\boldsymbol{n})$, as well as the corresponding $a(\boldsymbol{n_{in}}, \boldsymbol{n})$ and $a(\boldsymbol{n}, \boldsymbol{n_{out}})$. Let's denote by $\boldsymbol{e}_{(k,q)}$ a unit vector of dimension of vector $\boldsymbol{n}$ containing 1 in the position corresponding to the component $n_{(k,q)}$ in vector $\boldsymbol{n}$, and zeros in the remaining positions. Any event of receipt or completion of the service of requests in the network corresponds to the difference of two unit vectors. For example, the receipt of a type k request corresponds to the transition of the network from state $\boldsymbol{n}$ to state $\boldsymbol{n} - \boldsymbol{e}_{(0,q)} + \boldsymbol{e}_{(k,q)}$, i.e. the ST group, in which real-time requests are not serviced, and the service of data transfer is in the q state, is reduced by one ST, and one ST is added to the ST group, in which k-type requests are serviced and the service of data transfer is in the q state. Possible transitions in the network between states, their conditions and intensities are characterized by Table 1, where it is assumed that the network is in state $\boldsymbol{n}$.

Table 1

Possible transitions between network states

The event that caused the transition	Transition conditions	
	Changing the state of the ST	Network state change, conditions, transition intensity (coefficients in SEE)
Transitions to state $\boldsymbol{n}$ (set $S_{in}(\boldsymbol{n})$)		
Entering state $\boldsymbol{n}$ when requests are received		
Type k request	$(0,q) \to (k,q)$, $k = 1,2,\dots,K$	$\boldsymbol{n} + \boldsymbol{e}_{(0,q)} - \boldsymbol{e}_{(k,q)} \to \boldsymbol{n}$, $n_{(k,q)} > 0$, $\left(n_{(0,q)} + 1\right) \beta_k$
Request for data transfer	$(k,0) \to (k,1)$, $k = 0,1,\dots,K$	$\boldsymbol{n} + \boldsymbol{e}_{(k,0)} - \boldsymbol{e}_{(k,1)} \to \boldsymbol{n}$, $n_{(k,1)} > 0$, $\left(n_{(k,0)} + 1\right)\beta_e$
Entering state $\boldsymbol{n}$ when the request service is completed		
Type k request	$(k,q) \to (0,q)$ $k = 1,2,\dots,K$	$\boldsymbol{n} - \boldsymbol{e}_{(0,q)} + \boldsymbol{e}_{(k,q)} \to \boldsymbol{n}$, $\boldsymbol{n} \in S \backslash U_k$, $n_{(0,q)} > 0$ $\left(n_{(k,q)} + 1\right)\mu_k$
Request for data transfer	$(k,1) \to (k,0)$, $k = 0,1,\dots,K$	$\boldsymbol{n} - \boldsymbol{e}_{(k,0)} + \boldsymbol{e}_{(k,1)} \to \boldsymbol{n}$, $\boldsymbol{n} \in S \backslash U_e$, $n_{(k,0)} > 0$, $\left(n_{(k,1)} + 1\right)\mu_e^k$ $\left(\boldsymbol{n} - \boldsymbol{e}_{(k,0)} + \boldsymbol{e}_{(k,1)}\right)$
Transitions from state $\boldsymbol{n}$ (set $S_{out}(\boldsymbol{n})$)		
Exit from state $\boldsymbol{n}$ when requests are received		
Type k request	$(0,q) \to (k,q)$ $k = 1,2,\dots,K$	$\boldsymbol{n} \to \boldsymbol{n} - \boldsymbol{e}_{(0,q)} + \boldsymbol{e}_{(k,q)}$, $\boldsymbol{n} \in S \backslash U_k$, $n_{(0,q)} > 0$, $n_{(0,q)}\beta_k$
Request for data transfer	$(k,0) \to (k,1)$, $k = 0,1,\dots,K$	$\boldsymbol{n} \to \boldsymbol{n} - \boldsymbol{e}_{(k,0)} + \boldsymbol{e}_{(k,1)}$, $\boldsymbol{n} \in S \backslash U_e$, $n_{(k,0)} > 0$, $n_{(k,0)}\beta_e$
Exit from state $\boldsymbol{n}$ when the request service is completed		
Type k request	$(k,q) \to (0,q)$, $k = 1,2,\dots,K$	$\boldsymbol{n} \to \boldsymbol{n} + \boldsymbol{e}_{(0,q)} - \boldsymbol{e}_{(k,q)}$, $n_{(k,q)} > 0$, $n_{(k,q)}\mu_k$
Request for data transfer	$(k,1) \to (k,0)$, $k = 0,1,\dots,K$	$\boldsymbol{n} \to \boldsymbol{n} + \boldsymbol{e}_{(k,0)} - \boldsymbol{e}_{(k,1)}$, $n_{(k,1)} > 0$, $n_{(k,1)}\mu_e^k(\boldsymbol{n})$

The table contains the function $\mu_e^k(\boldsymbol{n})$, which makes sense of the intensity of servicing data transfer requests for ST groups that either served only such requests (case $k = 0$), or simultaneously served requests for real-time traffic transmission of type k with data transfer requests. Let's define $\mu_e^k(\boldsymbol{n})$. For convenience, we will assume that the numbers of real-time services are numbered in the order of increasing the b_k parameter, i.e. $b_1 \le b_2 \le \dots \le b_K$. At the same time, the maximum possible resource for servicing requests for data traffic transmission, when all ST are operating at maximum speed, is obviously $v_{etm} = n_{(0,1)}b_{max} + n_{(1,1)}(b_{max} - b_1) + n_{(2,1)}(b_{max} - b_2) + \dots + n_{(K,1)}(b_{max} - b_K)$. At the same time, in the network at state $\boldsymbol{n}$, the resource for servicing data traffic is $v_{et} = v - l + b_e \sum_{k=0}^{K} n_{(k,1)}$. There are two possible cases here. If $v_{et} \ge v_{etm}$, then the maximum possible resource can be assigned to each ST, taking into account the requests for real-time traffic transmission, and $\mu_e^0(\boldsymbol{n}) = \mu_e {}^{b_{max}}\!/_{b_e}$, $\mu_e^1(\boldsymbol{n}) = \mu_e {}^{(b_{max} - b_1)}\!/_{b_e}, \dots,$ $\mu_e^K(\boldsymbol{n}) = \mu_e {}^{(b_{max} - b_K)}\!/_{b_e}$. If $v_{et} < v_{etm}$, then the following procedure is performed:

1) Put $L = K$.

2) If $\sum_{k=0}^{L} n_{(k,1)} > 0$, calculate the value of resources for the maintenance of the requests with a uniform distribution between ST $b_{unf} = \left\lfloor {}^{v_{et}}\!/_{\left(\sum_{k=0}^{L} n_{(k,1)}\right)} \right\rfloor$, otherwise the end of the procedure.

3) If $b_{unf} \le (b_{max} - b_L)$, it is assumed that $\mu_e^1(\boldsymbol{n}) = \mu_e^2(\boldsymbol{n}) = \dots = \mu_e^L(\boldsymbol{n}) = \mu_e b_{unf}/b_e$. The end of the procedure.

4) Assign $\mu_e^L(\boldsymbol{n}) = \mu_e {}^{(b_{max} - b_L)}\!/_{b_e}$ and $v_{et} \coloneqq v_{et} - n_{(L,1)}(b_{max} - b_L)$.

5) Put $L \coloneqq L - 1$ and, if $L \ge 0$, go to step 2), otherwise the end of the procedure.

Note that the rows of Table 1 are taken into account when forming each equation from the SEE several times. For example, the first line, entering state $\boldsymbol{n}$ when k-type requests are received, can be counted up to $2k$ times, i.e. up to k times for the case $q = 0$ and up to k times for the case $q = 1$. The transition is included in the equation when the condition $n_{(k,q)} > 0$ is met. The second line, entering state $\boldsymbol{n}$ when data transfer requests are received, can be counted up to $(k+1)$ times, etc.

To solve the SEE, following the approaches developed in [5], we will use the Gauss-Seidel method. The Gauss-Seidel recursion linking the estimation of the non-normalized probabilities of the states of successive (s-th and (s+1)-th) steps of the iterative process, taking into account (4), will have the form:

$$P^{(s+1)}(\boldsymbol{n}) = \\ = \left(\sum_{\boldsymbol{n_{in}} \in S_{in}(\boldsymbol{n})} P^{(s,s+1)}(\boldsymbol{n_{in}}) a(\boldsymbol{n_{in}}, \boldsymbol{n}) \right) \Bigg/ \left(\sum_{\boldsymbol{n_{out}} \in S_{out}(\boldsymbol{n})} a(\boldsymbol{n}, \boldsymbol{n_{out}}) \right), \boldsymbol{n} \in S \quad (5)$$

Here, estimates of non-normalized probabilities, unlike normalized ones, are indicated by a capital letter P. The upper index corresponds to the step number, and the double index (s, s + 1) means that not only the results of calculations of step s are used for evaluation, but also the components of the evaluation vector already calculated at (s + 1) step. The convergence of the method is estimated based on the achievement of a small (at the level of 10^{-8} – 10^{-10}) normalized difference between two successive approximations to the vector of unknown probabilities [5]. The probabilities $p(\boldsymbol{n})$, $\boldsymbol{n} \in S$, are obtained by normalization:

$$p(\boldsymbol{n}) = \frac{P(\boldsymbol{n})}{N}, N = \sum_{\boldsymbol{n} \in S} P(\boldsymbol{n}) \quad (6)$$

The calculated probabilities $p(\boldsymbol{n})$, $\boldsymbol{n} \in S$, allow us to obtain the values of quality indicators. Let's start by defining the indicators for a particular LA. It should be noted that the loss of requests in the network can be estimated both from the position of the operator and from the position of the user of communication services [5]. Let's limit ourselves to an assessment from the user's point of view.

Since the input traffic in the considered network depends on its state $\boldsymbol{n}$, the proportion of requests for the transmission of traffic of each type lost due to the lack of a free channel resource should be estimated as the ratio of the intensity of the lost requests of the corresponding stream to the intensity of the received requests of this stream [5]. For k-type real-time traffic service requests, we get

$$\pi_k = \frac{\sum_{\boldsymbol{n}\in U_k}\left(p(\boldsymbol{n})\left(n_{(0,0)}+n_{(0,1)}\right)\right)}{\sum_{\boldsymbol{n}\in S}\left(p(\boldsymbol{n})\left(n_{(0,0)}+n_{(0,1)}\right)\right)}, \qquad (7)$$

and for data transfer requests

$$\pi_e = \frac{\sum_{\boldsymbol{n}\in U_e}\left(p(\boldsymbol{n})\sum_{k=0}^{K} n_{(k,0)}\right)}{\sum_{\boldsymbol{n}\in S}\left(p(\boldsymbol{n})\sum_{k=0}^{K} n_{(k,0)}\right)}, \qquad (8)$$

The average service time of a data transfer request is calculated using Little's formula as the ratio of the average number of serviced data requests y_e to the intensity $\lambda_e(1-\pi_e)$ of the flow of data transfer requests accepted for service, and is equal to:

$$W = \frac{y_e}{\lambda_e(1-\pi_e)}$$

$$y_e = \sum_{\boldsymbol{n}\in S}\left(p(\boldsymbol{n})\sum_{k=0}^{K} n_{(k,1)}\right) \qquad (9)$$

$$\lambda_e = \beta_e \sum_{\boldsymbol{n}\in S}\left(p(\boldsymbol{n})\sum_{k=0}^{K} n_{(k,0)}\right).$$

Since in the network under consideration, ST are located in several LA with numbers m= 1,2, ...,M, then the quality indicators should be calculated as weighted averages on a set of LA. Belonging to a particular LA will be indicated by the upper index m. The average service time of a data transfer request in the W_c network is determined by the ratio:

$$W_c = \frac{1}{\lambda_{ce}}\sum_{m=1}^{M}\lambda_e^m\,(1-\pi_e^m)W^m,$$

$$\lambda_{ce} = \sum_{m=1}^{M}\lambda_e^m\,(1-\pi_e^m). \qquad (10)$$

Taking into account (9), we obtain

$$W_c = \frac{\sum_{m=1}^{M} y_e^m}{\lambda_{ce}}. \qquad (11)$$

3 Characteristics of the tasks that can be solved using the developed model

The developed model can be used to determine the minimum required resource and solutions for its distribution between LA in multiservice networks of low-power ST based on HTS. The initial data for solving the tasks are:

– he number of ST in each LA $N^m, m = 1,2,\dots,M$;

– the maximum transfer speed of ST in units of resource b_{max};

– a list of real-time services, their characteristics (b_k, μ_k, $k = 1,2,\dots,K$);

– haracteristics of elastic data traffic (b_e, μ_e);

– requirements for the quality of service provision ($\pi_k \le \pi_k^*$, $k = 1,2,\dots,K$, $\pi_e \le \pi_e^*$ и $W^m \le W^*$, $m = 1,2,\dots,M$);

– the intensity of occurrence of requests for each type of β_k, $k = 1,2,\dots,K$ and β_e at ST.

Note that for given ST characteristics, the quality indicators for individual LA π_k^m, $k = 1,2,\dots,K, \pi_e^m$, W^m, as well as λ_e^m and y_e^m, $m = 1,2,\dots,M$, are functions of the number of ST N^m and the allocated LA resource v^m, $m = 1,2,\dots,M$. This allows you to use two-step procedures to solve tasks. At the first step, the dependencies π_k^m, π_e^m, W^m, λ_e^m and y_e^m are obtained from the possible values of v^m for given N^m, $m = 1,2,\dots,M$, and at the second step, on the basis of these dependencies, preferred solutions for the network as a whole are found.

The task of minimizing the required resource has the form:

$$\begin{gathered} v = \sum_{m=1}^{M} v^m \to \min, \\ \pi_k^m(v^m,N^m) \le \pi_k^*, m = 1,2,\dots,M, k = 1,2,\dots,K, \\ \pi_e^m(v^m,N^m) \le \pi_e^*,\ W^m(v^m,N^m) \le W^*, \\ m = 1,2,\dots,M. \end{gathered} \qquad (12)$$

Obviously, the total resource will be minimal if the minimum resources provided by each LA. Therefore, to solve the task, first for each LA $(m = 1,2,\dots,M)$ using the dependencies $\pi_k^m(v^m,N^m)$, $\pi_e^m(v^m,N^m)$, $W^m(v^m,N^m)$ it is necessary to find the minimum resource values v_k^m, v_e^m and v_w^m, that satisfy the corresponding constraints (12). Then v^m is obtained in the form $v^m = \max(v_k^m, v_e^m, v_w^m)$, and $v = \sum_{m=1}^{M} v^m$.

We will consider the task of finding the preferred distribution of resource v between LA in two formulations. The first one provides for minimizing the average service time of a data transfer request in the network W_c and, taking into account (10) and (11), has the form:

$$\begin{gathered} W_c = \frac{\sum_{m=1}^{M} y_e^m\,(v^m,N^m)}{\sum_{m=1}^{M} \lambda_e^m\,(v^m,N^m)\left(1-\pi_e^m(v^m,N^m)\right)} \to \min, \\ \sum_{m=1}^{M} v^m = v, \\ \pi_k^m(v^m,N^m) \le \pi_k^*, m = 1,2,\dots,M, k = 1,2,\dots,K, \\ \pi_e^m(v^m,N^m) \le \pi_e^*,\ W^m(v^m,N^m) \le W^*, \\ m = 1,2,\dots,M. \end{gathered} \qquad (13)$$

The second formulation proceeds from the fact that ST of all LA should have equal opportunities for data transmission, and, accordingly, the maximum average service time of a data transfer request on a set of LA is subject to minimization:

$$\begin{gathered} \max_{m\in 1,M}\left(\frac{y_e^m(v^m,N^m)}{\lambda_e^m(v^m,N^m)\left(1-\pi_e^m(v^m,N^m)\right)}\right) \to \min, \\ \sum_{m=1}^{M} v^m = v, \\ \pi_k^m(v^m,N^m) \le \pi_k^*, m = 1,2,\dots,M, k = 1,2,\dots,K, \\ \pi_e^m(v^m,N^m) \le \pi_e^*,\ W^m(v^m,N^m) \le W^*, \\ m = 1,2,\dots,M. \end{gathered} \qquad (14)$$

When solving tasks in both formulations, you should first find the minimum resources of the LA $v_{min}^m, m = 1,2,\dots,M$, ensuring the fulfillment of restrictions on the limit values of quality indicators. In fact, the resource $v_\text{p} = v - \sum_{m=1}^{M} v_{min}^m$ is subject to distribution between LA.

Since the solutions of SEE and the values of quality indicators can only be obtained numerically, a direct search seems natural to solve tasks. Obviously, the number of variants is equal to the number of combinations from $\left(v_\text{p} + M - 1\right)$ to $(M-1)$, i.e. $C_{v_\text{p}+M-1}^{M-1}$. Direct search can be used when v_p and M are small. For example, if the ST are located in seven LA, and the volume of the unallocated resource is 30-40 units, then it is necessary to calculate about 2-10 million variants. If the dependencies of quality indicators and parameters for individual LA are calculated in advance in the form of tables, then such a search is not difficult for a personal computer.

If the intensity of the flow of requests of each type can be approximately considered constant (as in the Erlang model), and the loss of data transmission costs is negligible, the dynamic programming method can be used to solve the task in the first formulation [12] by analogy with how it is done in [11].

Regarding the solution of the task in the second formulation, it is necessary to note that the dependencies of the average service time of the request for data transfer on the resource for each LA are non-increasing (see an example of such dependencies in Figure 4). In these conditions, the resource should be distributed step by step, sending the next unit to the LA, where the current achieved average service time is maximum.

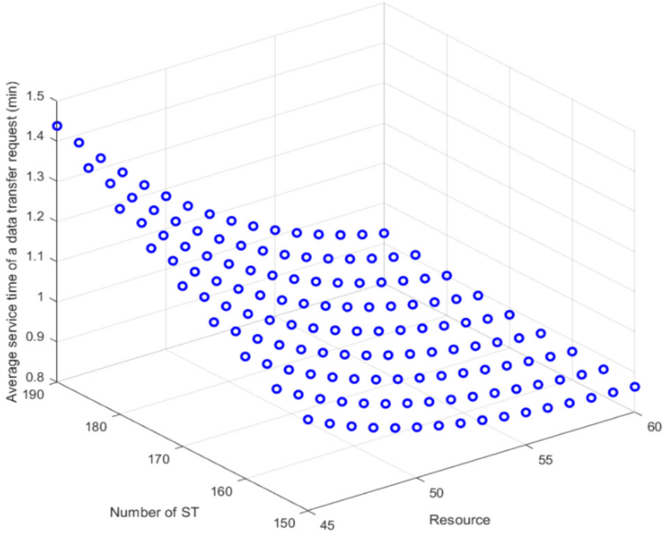

Fig. 4. Example of the dependencies of the average service time of a data transfer request on a resource allocated to the LA for a different number of ST

Taking into account the above circumstances, the generalized schemes for solving tasks (12), (13) and (14) include the following steps:

1) Construction for each LA of the dependencies $\pi_k^m (k = 1,2, \dots, K)$, π_e^m, W^m, λ_e^m and y_e^m on the possible values of v^m for given $N^m, m = 1,2, \dots, M$. Finding the minimum values of v_{min}^m from them, ensuring the fulfillment of the constraints of the corresponding tasks (12), (13) or (14), as well as the value of the distributed resource v_p for tasks (13) and (14). The vector $(v_{min}^1, v_{min}^2, \dots, v_{min}^M)$ is the solution to task (12). And for tasks (13) and (14), the upper bounds of the LA resource values for dependencies are expanded to $v_{min}^m + v_\text{p}$.

2) Acceptance of minimum values for tasks (13) and (14) as initial resource values $(v^m = v_{min}^m, m = 1,2, \dots, M)$.

3) When solving the task (14) performing v_p steps, including:

– determination of the number of LA with a maximum value $W^m(v^m, N^m)$, i.e. $m = \underset{m \in [1,M]}{\operatorname{argmax}} W^m(v^m, N^m)$ where $W^m(v^m, N^m)$ is calculated according to (14);

– allocation of the resource unit of the m-th LA $(v^m \coloneqq v^m + 1)$.

4) When solving task (13), the following steps are performed:

– generation of a set of variants $G\left(M, v_\text{p}\right)$ for allocating an additional resource v_p to an existing set of M LA. The generation is carried out step by step. Obviously, $G(M,1)$ includes M variants (the resource unit is transferred to one of the M LA). $G(M,i)$ is obtained from $G(M,i-1)$ by adding to each variant from $G(M,i-1)$ a unit of resource in one of the LA (M variants) and filtering out the matching variants;

– calculation of the objective function of the task (13) for each variant of $G\left(M, v_\text{p}\right)$ and determination of the variant providing a minimum of W_c.

4 Numerical examples of the use of model

As an example, consider the case of placing ST in three LA, with $N^1 = 50, N^2 = 100$ and $N^3 = 150$. Maximum transfer rate ST in resource units $b_{max} = 8$. Two real-time services with parameters are available to drivers: $b_1 = 1, b_2 = 4, \mu_1 = 0{,}3$ min^{-1}, $\mu_2 = 0{,}15$ min^{-1}, as well as elastic traffic transmission services with parameters $b_e = 2$, $\mu_e = 0{,}3$ min^{-1}. The intensity of occurrence at each ST of requests for real-time traffic $\beta_1 = 0{,}03$ min^{-1}, $\beta_2 = 0{,}002$ min^{-1}, and for elastic data traffic $\beta_e = 0{,}01$ min^{-1}. Let the quality-of-service requirements be set in the form $\pi_1 = \pi_2 = \pi_e \leq 0{,}01$.

In accordance with the task solving scheme described in the third section, the dependencies of the service parameters for each LA on the allocated resource are first obtained. Figure 5 shows the dependencies for the second real-time service $\pi_2^1(v^1)$, $\pi_2^2(v^2)$ and $\pi_2^1(v^3)$, since this service requires maximum resource costs to service requests. The dependencies $W^1(v^1)$, $W^2(v^2)$ and $W^3(v^3)$ are shown in Figure 6.

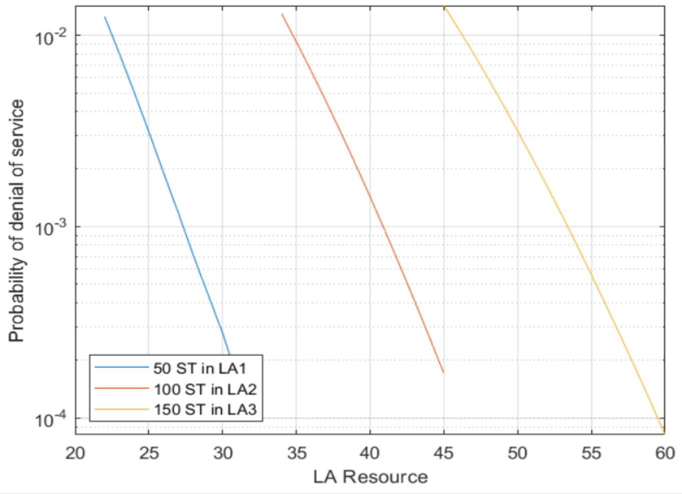

Fig. 5. Dependence of the probabilities of denial of service for requests of the second real-time service on the amount of resource allocated to the LA

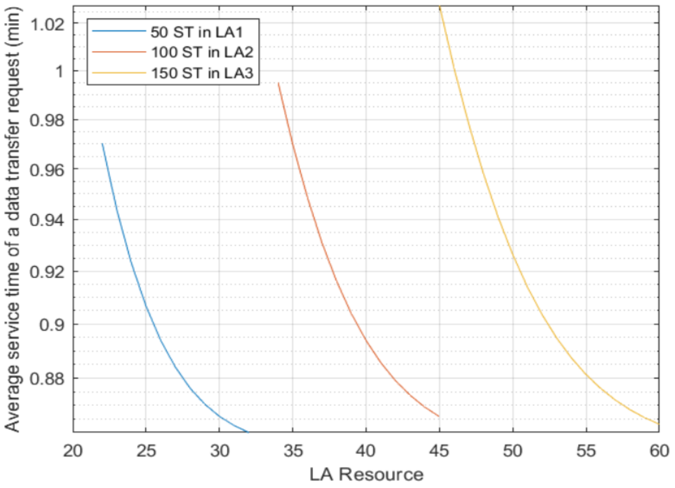

Fig. 6. Dependence of the average service time (in minutes) of requests for the transmission of elastic data traffic (ET) on the volume of the resource allocated to the LA

Figure 6 shows that the minimum LA resources are $v^1_{мин}$ =23, $v^2_{мин}$ =35 и $v^3_{мин} = 47$. Therefore, the minimum network resource is 105.

Suppose that during operation the network resource is 115 units, i.e. $v_p = 10$. Solving the task in formulation (14), we obtain:

– minimum average time 0,91392 min.;

– L resources v^1 =25, v^2 =39 and v^3 =51.

To solve the task in formulation (13), a set of variants has been formed with a total number of $C^2_{12} = 66$. Comparing the variants gives the result:

– minimum average time is 0,90591min.;

– L resources v^1 =23, v^2 =39 and v^3 =53.

The difference in the results can be explained by the fact that in order to minimize the average time for servicing requests for data traffic transmission over the network, it is preferable to invest the resource in the third LA, from where the main part of the request flow comes, allowing some increase in the average time for the first LA, from where the flow is minimal.

5 Conclusion

For networks of low-power subscriber terminals based on HTS, a model of joint maintenance of real-time multiservice traffic and elastic data traffic has been built, taking into account the uneven placement of terminals in local areas, a limited number of terminals, the possibility of simultaneous servicing by each terminal of requests for traffic transmission of two types, one of them which is elastic data traffic, another real-time traffic, with a limit on the speed of information transfer by the terminal. When constructing the model, the apparatus of multidimensional stepwise Markov processes and the Gauss-Seidel method were used to find the probabilities of network states in steady-state mode. Using the model, both the tasks of determining the minimum required network resource to meet the specified quality requirements can be solved, as well as the tasks of finding preferred resource distributions between local areas according to the criterion of minimizing the average service time for data transfer requests. The results obtained make it possible to use the model in planning and managing the operation of networks based on spacecraft with high throughput.

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МОДЕЛИ ПРОЦЕССОВ СОВМЕСТНОГО ОБСЛУЖИВАНИЯ МУЛЬТИСЕРВИСНОГО ТРАФИКА РЕАЛЬНОГО ВРЕМЕНИ И ЭЛАСТИЧНОГО ТРАФИКА ДАННЫХ В СЕТИ МАЛОМОЩНЫХ МОБИЛЬНЫХ АБОНЕНТСКИХ ТЕРМИНАЛОВ НА БАЗЕ КА С ВЫСОКОЙ ПРОПУСКНОЙ СПОСОБНОСТЬЮ

Маслов Александр Александрович, *Московский физико-технический институт (национальный исследовательский университет), Москва, Россия,* **maslov.aa@mipt.ru**
Себекин Геннадий Валерьевич, *Московский физико-технический институт (национальный исследовательский университет), Москва, Россия,* **sebekin.gv@mipt.ru**
Степанов Сергей Николаевич, *Московский технический университет связи и информатики; Институт радиотехники и электроники им. В.А.Котельникова Российской академии наук (ИРЭ им. В.А.Котельникова РАН), Москва, Россия,* **s.n.stepanov@mtuci.ru**
Щурков Алексей Олегович, *Московский физико-технический институт (национальный исследовательский университет), Москва, Россия,* **shchurkov.ao@mipt.ru**
Васильев Александр Проталионович, *Московский технический университет связи и информатики, Москва, Россия*

Аннотация

Для реализации функций планирования и распределения канального ресурса в сетях маломощных мобильных абонентских терминалов на базе космических аппаратов с высокой пропускной способностью на геостационарной и высокоэллиптических орбитах требуется разработка моделей процессов совместного обслуживания мультисервисного трафика реального времени и эластичного трафика данных. Модели должны учитывать неравномерность размещения терминалов по локальным зонам, ограниченное их количество, возможность одновременного обслуживания каждым терминалом заявок на передачу трафика двух типов, один из которых является эластичным трафиком данных, другой трафиком реального времени, при ограничении на скорость передачи информации терминалом. Цель работы состоит в решении задачи моделирования с учетом перечисленных факторов. Построены модели на основе многомерных ступенчатых марковских процессов. Определен перечень задач, которые могут решаться с их использованием, включающий как задачи определения минимально необходимого ресурса сети для выполнения заданных требований по качеству, так и задачи отыскания предпочтительных распределений ресурса между локальными зонами по критерию минимизации среднего времени обслуживания заявок на передачу данных. Представлены численные примеры решения каждой задачи. Разработанные модели могут быть использованы для построения систем управления сетью передачи информации на базе космических аппаратов с высокой пропускной способностью.

Ключевые слова: *космические аппараты с высокой пропускной способностью, канальный ресурс, мультисервисный трафик, трафик реального времени, эластичный трафик, мобильные абонентские терминалы.*

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