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Model for Servicing Multiservice Traffic in an Access Node of a Satellite Communications Network with a Dynamically Variable Service Delivery Rate

A. A. Maslov[*,a], **G. V. Sebekin**[*,b], **M. S. Stepanov**[**,c], **S. N. Stepanov**[**,d], and **A. O. Shchurkov**[*,e]

[*] *Moscow Institute of Physics and Technology (National Research University), Moscow, Russia*
[**] *Moscow Technical University of Communications and Informatics, Moscow, Russia*
e-mail: [a]*maslov.aa@mipt.ru,* [b]*sebekin.gv@mipt.ru,* [c]*m.s.stepanov@mtuci.ru,*
[d]*s.n.stepanov@mtuci.ru,* [e]*shchurkov.ao@mipt.ru*

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Abstract—In multi-service satellite communication networks, as a rule, it is possible to provide a particular service with different quality, while using different traffic transfer rates. Accordingly, license agreements may stipulate that a particular service is provided at a certain speed for the majority of the time, and it is acceptable to reduce the speed to the maximum threshold in the remaining time. At the same time, network operators need a mathematical apparatus that allows them to evaluate the fulfillment of the requirements specified in the agreements in order to have an idea to what extent it is possible to expand the subscriber capacity of the network. The article develops a mathematical model of joint maintenance in access nodes of such networks of real-time service traffic and elastic data traffic based on the formalization of the network operation process using the apparatus of multidimensional stepwise Markov processes. Examples of solving the problems of determining the required resource at the network planning stage and evaluating the possibility of expanding the subscriber capacity of the network with the available resource are given.

Keywords: spacecraft, channel resource, multi-service traffic, real-time traffic, elastic traffic, multidimensional stepwise Markov processes

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1. INTRODUCTION

In multi-service satellite communication networks (Fig. 1), where the role of subscriber access nodes to terrestrial network and Internet services is played by central earth stations (CES) together with spacecraft (SC), there is typically the possibility of providing one or another service at different transmission rates. The higher the speed, the better the quality, for example, clearer video images, etc.

Since the bandwidth of satellite channels is limited, when there is a large number of simultaneously served subscribers, using the highest possible speeds becomes impossible, and for some subscribers, a reduction in speed is required. Accordingly, licensing agreements (Service Level Agreements, or SLA) may stipulate that a specific service is to be provided at high speed for the majority of the time, while a reduction to a minimum threshold is permitted for the remaining time. In such cases, network operators require a mathematical framework to evaluate compliance with the specified SLA requirements. This framework is essential for determining to what extent the subscriber capacity of the network can be expanded under the given constraints, or when further

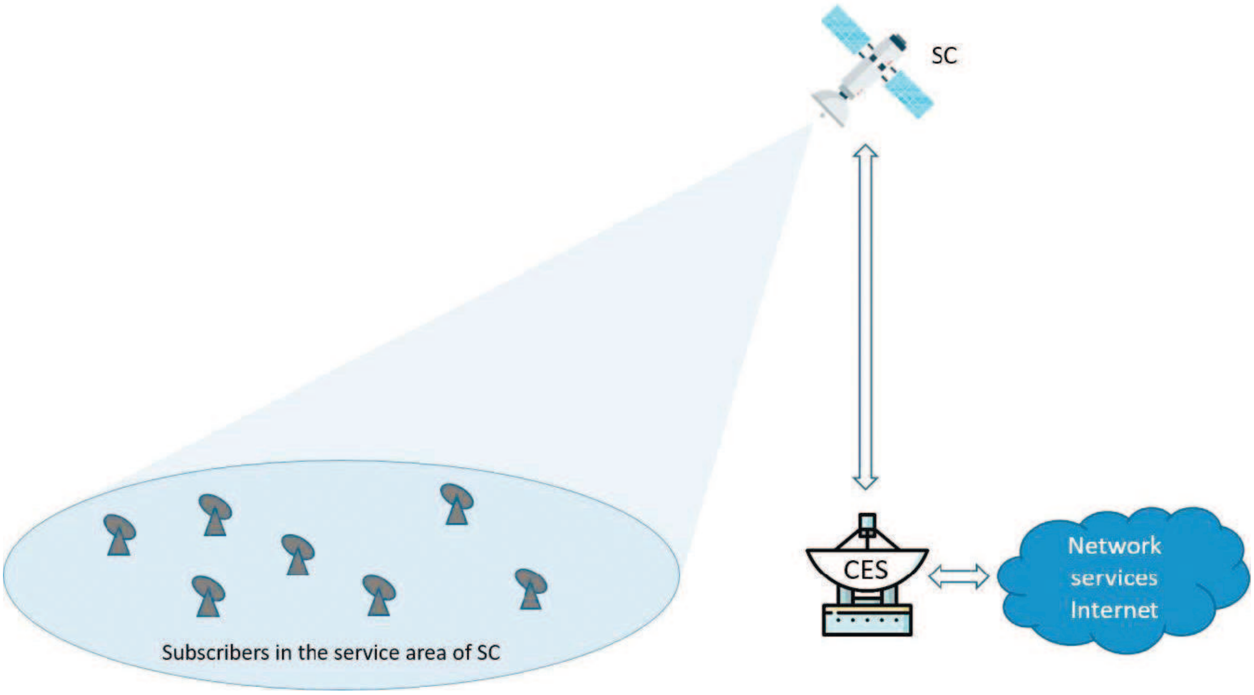

Fig. 1. Simplified diagram of a multi-service satellite communication network.

expansion becomes impossible, necessitating network upgrades, adjustments to standards, changes in tariff policies, and so forth.

This article addresses this task by considering an access node of a multi-service network. The quality of service (QoS) in this network is assessed by the following indicators:

- The high transmission rates for each service's traffic, ensuring the best quality.
- The fractions of time during which the service traffic is transmitted at high rates.
- The minimum allowable transmission rates for each service's traffic for the remaining time.
- The fractions of lost requests of each type due to insufficient resources.
- The average file delivery time.

It is assumed that the network handles K types of real-time (RT) service traffic and elastic data service traffic. The resource for servicing requests is allocated in discrete units of speed quanta.

The quantum, Δv, is measured in bits/s. The network infrastructure within the Central Earth Station (CES) includes a connection management system. This system implements rules that uniquely determine how resources are assigned and redistributed upon the arrival and completion of service requests, taking into account the current network state. A service request is accepted only if the available resource is sufficient to service all current requests, at least at their minimum speeds. Any remaining resource is then used to assign high service speeds to some or all of the requests, based on the importance of the corresponding service types and the volume of the remaining resource. Finally, any leftover resource, if present, is allocated to increase the speed of elastic traffic. Consequently, for elastic traffic, the high and minimum speeds specified in the SLA are effectively guaranteed and can be exceeded. Furthermore, while the session duration for RT traffic is independent of its transmission rate, the file delivery time decreases as the rate increases.

The purpose of this article is to develop a mathematical model for a multi-service satellite network access node. This model accounts for the ability to change the transmission rates of individual services and enables the evaluation of the aforementioned quality of service indicators for each traffic type.

Modeling of multi-service networks is usually carried out under the assumption that the flows of requests in the network are Poisson, and the service durations are exponentially distributed. This allows building analytical models using the apparatus of multidimensional stepwise Markov processes. A wide range of works is devoted to the development of models for multi-service networks. Fundamental results are presented, for example, in [1–5]. A large number of results have been obtained for networks of various purposes [6–23], including multi-service satellite networks [16–23], including networks based on spacecraft in geostationary and highly elliptical orbits [16–19], [22], as well as in low circular orbits [20, 21]. Although the factor of transmission rate change in most works was taken into account only for elastic traffic, the possibilities of adjusting the rate in a certain range for real-time traffic were also considered, for example in [15]. However, different quality indicators from those mentioned above were taken into account. So in [15] the goal is to analyze the average data transmission rate of video conferences. Therefore, the task of modeling a network access node is relevant.

To achieve this goal, Section 2 describes the model, Section 3 formulates and solves the system of equilibrium equations of the Markov process describing the dynamics of network state changes, and obtains relations for calculating quality indicators. Section 4 provides a numerical analysis of the model characteristics.

2. MODEL DESCRIPTION

In the considered network, transmission of real-time service traffic (voice information, video conferencing data, etc.), depending on the service type, can be performed at high speeds V_k, $k = 1, \dots, K$, provided in the SLA, and at certain time intervals with a large number of active subscribers at minimally allowable speeds $V_k^{'}$. File transmission is carried out within elastic traffic and can be performed during the main part of the time at a speed not lower than the guaranteed high speed V_e and the rest of the time at a speed not lower than the minimally allowable $V_e^{'}$.

Let $b_k = \lceil V_k/\Delta v \rceil$, $k = 1, \dots, K$ and $b_e = \lceil V_e/\Delta v \rceil$ be the resources, expressed as an integer number of used speed quanta, required for transmitting RT and elastic traffic at high speeds V_k or V_e. Note that the resource for data transmission by one subscriber can be more than b_e. Let $b_k^{'} = \left\lceil V_k^{'}/\Delta v \right\rceil$, $k = 1, \dots, K$ and $b_e^{'} = \left\lceil V_e^{'}/\Delta v \right\rceil$ be the resources corresponding to the minimum speeds $V_k^{'}$ or $V_e^{'}$. Here also the resource for data transmission by one subscriber can be more than $b_e^{'}$.

Service RT with number $k = 1, \dots, K$ is received by N_k subscribers. The service time of a request for service is an exponentially distributed random variable with parameter μ_k. After the service of a request is completed, a new request from this subscriber arises after a random time, which has an exponential distribution with parameter β_k. The corresponding parameters for elastic traffic are denoted by N_e and β_e, and μ_e is the parameter of the exponential distribution of file transmission time when allocating resource b_e.

Let us introduce notations for quality indicators. Let P_k, $k = 1, \dots, K$, and P_e be the fractions of time during which the traffic of each RT service is transmitted at high speed, and elastic data traffic at a speed not less than the guaranteed high speed. Let π_k, $k = 1, \dots, K$, and π_e be the fractions of lost requests for service provision that were denied due to insufficient free resource upon their arrival, W be the average file delivery time, and v be the total network resource managed by the access node.

The dynamics of the network state change is described by the random process $r(t) = (i_1(t), \dots, i_K(t), d(t))$, where $i_k(t)$ is the number of serviced requests for service k and $d(t)$ is the number of serviced data requests at time t. The process is defined on the state space S, which includes states $s = (i_1, \dots, i_K, d)$ with integer non-negative components, each of which does not exceed the number of subscribers receiving the corresponding service. The space S can be written as

$$S = \left\{ (i_1, \ldots, i_K, d) : N_k \geqslant i_k \geqslant 0, k = 1, \ldots, \ K; N_e \geqslant d \geqslant 0; \sum_{k=1}^{K} i_k b_k^{'} + d b_e^{'} \leqslant v \right\}. \quad (1)$$

In this space, one can distinguish subsets of states U_k, $k = 1, \ldots, K$, and U_e, in which incoming requests for transmission of each type of real-time traffic and data traffic are denied due to insufficient resource for their service. These subsets are defined as follows:

$$U_k = \left\{ (i_1, \ldots, i_K, d) : \ (i_1, \ldots, i_K, d) \in S, \left(\sum_{k=1}^{K} i_k b_k^{'} + d b_e^{'} > v - b_k^{'} \right) \cup (i_k = N_k) \right\}, \quad (2)$$

$$U_e = \left\{ (i_1, \ldots, i_K, d) : \ (i_1, \ldots, i_K, d) \in S, \left(\sum_{k=1}^{K} i_k b_k^{'} + d b_e^{'} > v - b_e^{'} \right) \cup (d = N_e) \right\}. \quad (3)$$

To manage the network, the operator needs a rule $f(s)$ that unambiguously determines for each network state $s \in S$ the number of requests of each type $i_k^{(h)}$ out of i_k, $k = 1, \ldots, K$, and $d^{(h)}$ out of d, that will be serviced at high speed.

It should be noted that different networks have different lists of provided services, and the importance of each service is determined by the operator taking into account the target tasks solved by the network. Therefore, the choice of the rule $f(s)$ for resource allocation is qualitative and is not considered in the article. We will only assume that:

- interruption of request service is unacceptable;
- all requests of the same type have equal value;
- when applying the rule, the resource for traffic transmission at high speed is allocated for servicing requests in order of decreasing importance of their types, i.e., first for requests of the most important type, then for the next in importance, etc.

The rule $f(s)$ is executed when the network state changes and includes three stages:

- at the first stage, it is determined whether the resource is sufficient to service all requests at least at minimum speeds;
- if the resource is sufficient, at the second stage, high speeds are allocated for servicing requests taking into account the amount of free resource and the importance of service types;
- if there are remnants of free resource, they are directed to increase the transmission speed of elastic traffic.

A high-level algorithm for applying the rule is illustrated in Fig. 2. Commenting on the algorithm, we note that if any requests remain being serviced at minimum rates after the second stage, it is impossible to increase their speed to the high rate. Furthermore, allocating additional resources to requests whose traffic is already being transmitted at high speed is not efficient. Therefore, any remaining resource from the first two stages is allocated in the third stage to increase the transmission speed of elastic traffic.

It should also be noted that when new requests for important traffic types arrive, resources are allocated to them as a priority. For less important traffic types, if resources are insufficient, their transmission speed may be downgraded from high to minimum. In other words, a redistribution of the resources used for servicing different traffic types will occur.

A possible example of such a rule is considered in Section 4 when conducting numerical analysis.

Let us introduce the vector $s^{(h)} = (i_1^{(h)}, \ldots, i_K^{(h)}, d^{(h)})$. Then $s^{(h)} = f(s)$. Obviously, after assigning high service speeds to requests, the resource constraint must be satisfied, which is more

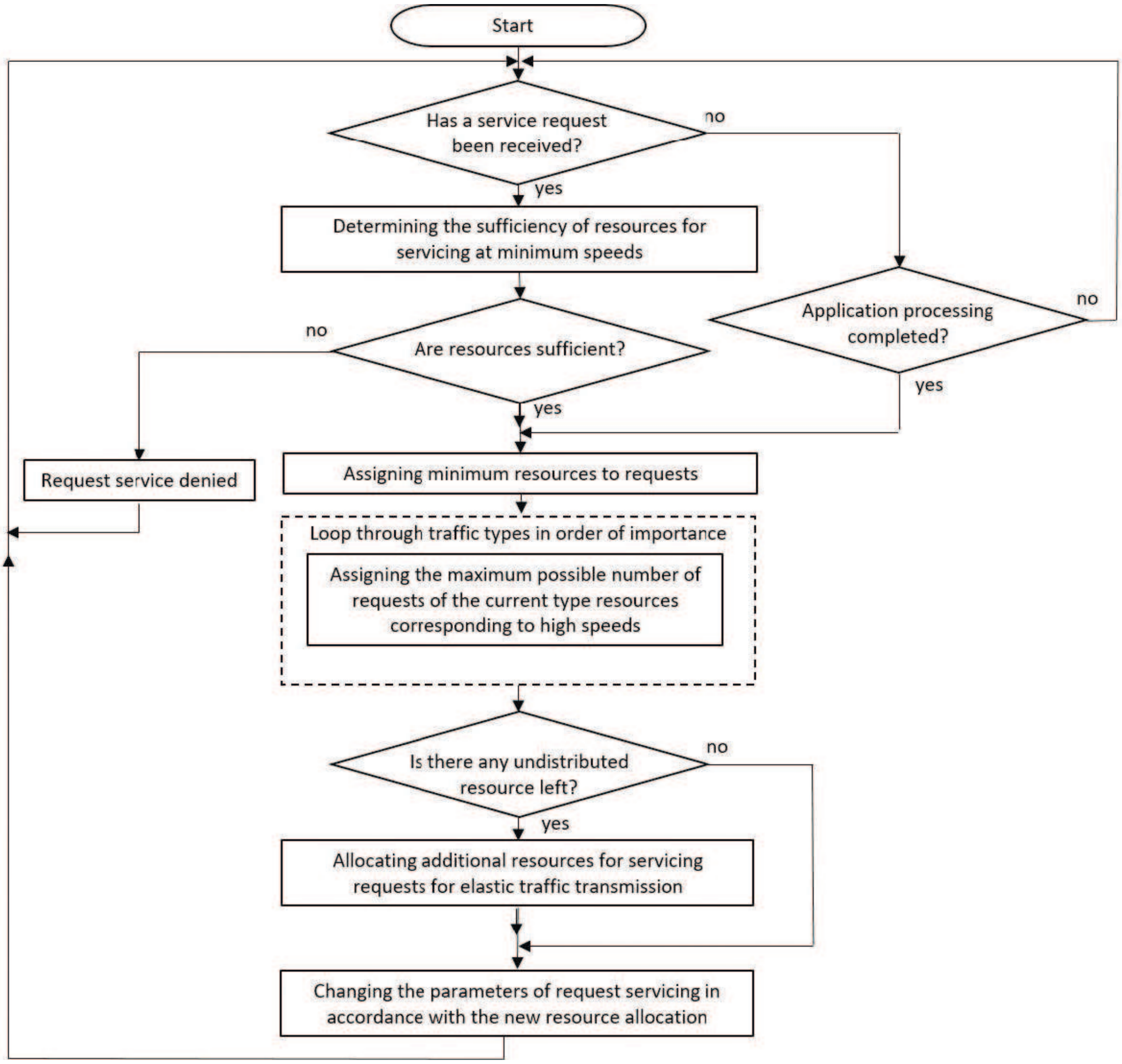

Fig. 2. High-level algorithm for applying the resource allocation rule.

stringent compared to the corresponding constraint in expression (1):

$$v_{\min} = \sum_{k=1}^{K} \left[\left(i_k - i_k^{(h)} \right) b_k' + i_k^{(h)} b_k \right] + \left(d - d^{(h)} \right) b_e' + d^{(h)} b_e \leqslant v. \tag{4}$$

If the network is servicing data requests, i.e., $d > 0$, and in expression (4) $v_{\min} < v$, then at the third stage of applying the rule $f(s)$ the residual resource in the amount of $v - v_{\min}$ is directed to service these requests. As a result, the total resource allocated for servicing data requests under the condition $d > 0$ is

$$v_e\left(s, s^{(h)}\right) = v - v_{\min} + \left(d - d^{(h)} \right) b_e' + d^{(h)} b_e, \tag{5}$$

and the total service intensity of such requests is

$$\mu_{et}\left(s, s^{(h)}\right) = \frac{v_e\left(s, s^{(h)}\right) \mu_e}{b_e}. \tag{6}$$

When events occur that change the network state, for the new state s, $s^{(h)} = f(s)$ is computed and resource redistribution between requests is performed, and expression (6) determines the intensity $\mu_{et}(s, s^{(h)})$ of leaving state s due to the event of file transmission completion.

3. SYSTEM OF EQUILIBRIUM EQUATIONS AND SERVICE PERFORMANCE MEASURES

Let $p(s)$ denote the probability of the network being in state $s \in S$, and $P(s)$ denote the unnormalized probability of that state. Unnormalized probabilities are used in iterative methods for solving systems of equilibrium equations (SEE). The connection between $p(s)$ and $P(s)$, taking into account the normalization condition, is as follows:

$$p(s) = \frac{P(s)}{\sum_{s\in S} P(s)}. \tag{7}$$

The SEE has the form:

$$\begin{aligned}
&P(i_1,\ldots,i_K,d)\Bigg[\sum_{k=1}^{K}\left(\beta_k\left(N_k-i_k\right)I\left((i_1,\ldots,i_K,d)\in S\backslash U_k\right)+i_k\mu_k\right)\\
&+\beta_e\left(N_e-d\right)I\left((i_1,\ldots,i_K,d)\in S\backslash U_e\right)+\mu_{et}\left(s,s^{(h)}\right)I(d>0)\Bigg]\\
&=\sum_{k=1}^{K}\Big[P\left(i_1,\ldots,i_k-1,\ldots,i_K,d\right)\beta_k\left(N_k-i_k+1\right)I\left(i_k>0\right)\\
&+P\left(i_1,\ldots,i_k+1,\ldots,i_K,d\right)\left(i_k+1\right)\mu_k I\left((i_1,\ldots,i_K,d)\in S\backslash U_k\right)\Big]\\
&+I(d>0)P\left(i_1,\ldots,i_K,d-1\right)\beta_e\left(N_e-d+1\right)\\
&+P\left(i_1,\ldots,i_K,d+1\right)\mu_{et}\left(s_d,s_d^{(h)}\right)I\left((i_1,\ldots,i_K,d)\in S\backslash U_e\right),\quad (i_1,\ldots,i_K,d)\in S.
\end{aligned} \tag{8}$$

The system of equations (8) is homogeneous, and the uniqueness of the solution is ensured by adding the normalization condition (7) to it. Here $s_d = (i_1, \ldots, i_K, d+1)$ and $s_d^{(h)} = f(s_d)$. The intensities $\mu_{et}\left(s, s^{(h)}\right)$ and $\mu_{et}\left(s_d, s_d^{(h)}\right)$ are computed according to relations (5) and (6). The indicator function $I(\text{condition } A)$ is also used, equal to 1 if the condition is satisfied and 0 otherwise.

The system of equations (8) can be solved numerically. The Gauss-Seidel method, described in [1] and used in a number of works, for example in [16–20], has proven itself well for solving such SEEs. This method is also used to obtain numerical results in Section 4.

Next, we proceed to obtain relations for calculating the quality of service indicators, interpreting the state probabilities $p(s)$, $s \in S$, as the fractions of time during which the network is in the corresponding states, i.e., over a sufficiently long time interval T, the network is in state s for approximately time $Tp(s)$. The total service time of i_k, $k = 1, \ldots, K$, requests for provision of the kth RT service in this state is $i_k Tp(s)$. At the same time, the vector of the number of requests serviced at high speeds is determined as $s^{(h)} = f(s)$, and the total service time of $i_k^{(h)} \leqslant i_k$ requests is $i_k^{(h)} Tp(s)$. Consequently, the fractions of time during which the traffic of each service is transmitted at high speed are determined as

$$P_k = \frac{\sum_{s\in S} i_k^{(h)} p(s)}{\sum_{s\in S} i_k p(s)}, \quad k = 1, \ldots, K. \tag{9}$$

Similarly for data requests:

$$P_e = \frac{\sum_{s\in S} d^{(h)} p(s)}{\sum_{s\in S} d p(s)}. \tag{10}$$

Since the input traffic in the considered network depends on its state s, the fraction of requests for transmission of each type of traffic lost due to lack of free channel resource should be estimated as the ratio of the intensity of lost requests of the corresponding flow to the intensity of arrived requests of this flow [1]. For requests for service of RT traffic of the kth type we obtain

$$\pi_k = \frac{\sum_{s\in U_k} (p(s)\,(N_k - i_k))}{\sum_{s\in S} (p(s)\,(N_k - i_k))}, \quad k = 1,\ldots,K, \tag{11}$$

and for data transmission requests

$$\pi_e = \frac{\sum_{s\in U_e} (p(s)\,(N_e - d))}{\sum_{s\in S} (p(s)\,(N_e - d))}. \tag{12}$$

The average file delivery time W can be determined using Little's formula as the ratio of the average number of simultaneously serviced data requests in the network y_e to the intensity λ_e of the flow of such requests accepted for service, and is equal to

$$W = \frac{y_e}{\lambda_e}, \tag{13}$$

$$y_e = \sum_{s\in S} dp(s), \tag{14}$$

$$\lambda_e = \beta_e \sum_{s\in S\setminus U_e} p(s)\,(N_e - d). \tag{15}$$

4. NUMERICAL ANALYSIS OF MODEL CHARACTERISTICS

As an example for numerical analysis, consider a three-service network of low-power mobile subscriber terminals based on high-throughput spacecraft [16, 17], serving two types of RT traffic and elastic data traffic. The traffic characteristics are presented in the table.

Table. System Parameters

Parameter	Value
Resource per request for RT service of the first type, $b_1/b_1^{'}$	1/1
Resource per request for RT service of the second type, $b_2/b_2^{'}$	8/4
Resource per data request, $b_e/b_e^{'}$	8/4
Number of users of RT service of the first type, N_1	150
Number of users of RT service of the second type, N_2	60
Number of data service users, N_e	120
Service intensity of requests for RT service of the first type, μ_1	0.3 min^{-1}
Service intensity of requests for RT service of the second type, μ_2	0.15 min^{-1}
Service intensity of data requests when allocating resource b_e, μ_e	1.2 min^{-1}
Parameter of exponential distribution of time until request arrival of the first type, β_1	0.06 min^{-1}
Parameter of exponential distribution of time until request arrival of the second type, β_2	0.009 min^{-1}
Parameter of exponential distribution of time until data request arrival, β_e	0.3 min^{-1}
Fraction of time during which RT service traffic is transmitted at the specified high speed, P_k, $k = 1, 2$, not less than	0.9
Fraction of time during which data service traffic is transmitted at a speed not lower than the specified threshold, P_e, not less than	0.9
Maximum allowable fractions of lost requests of each type due to insufficient resource	0.01
Average file delivery time, not more than	0.5 min

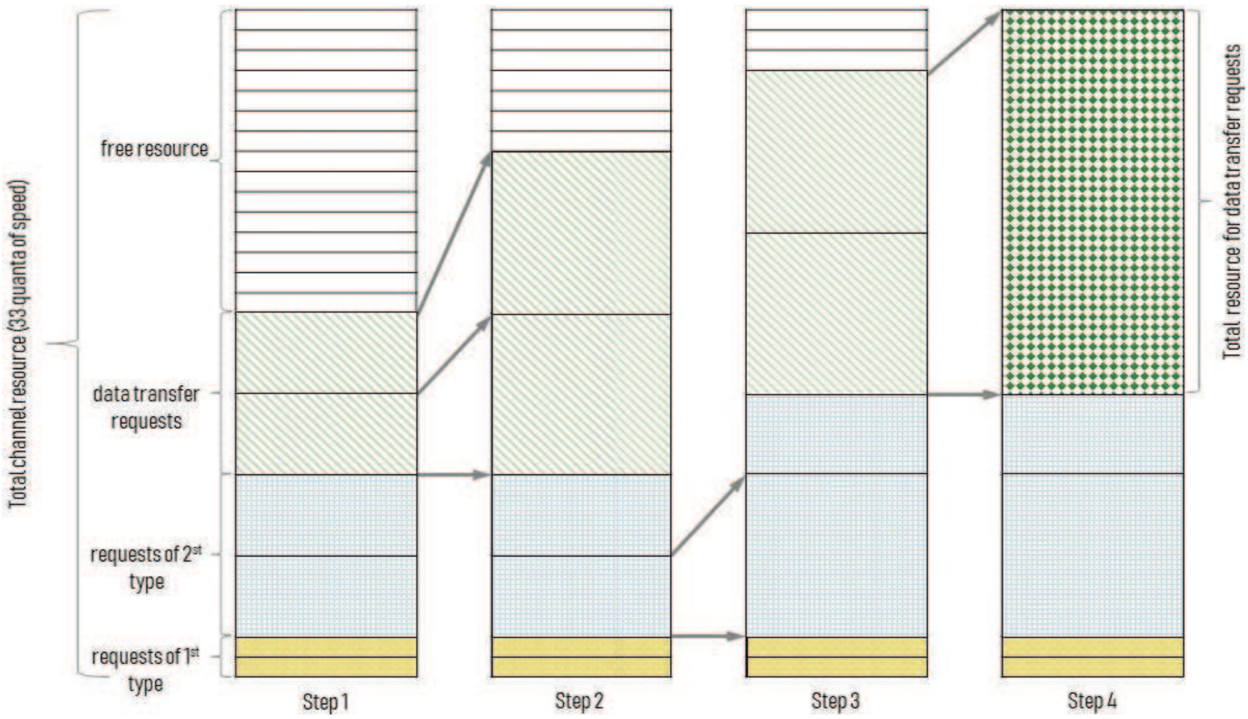

Fig. 3. Example of applying the resource allocation rule for a three-service network.

The rule $f(s)$ for assigning high speeds is based on the fact that ensuring high speed when servicing data requests is more important than for RT traffic of the second type, and RT traffic of the first type does not need speed increase, hence $b_1 = b_1^{'}$. At the same time, $f(s)$ carries out the following procedure:

- Determination of whether the resource is sufficient to service all requests when allocating them resources $b_1^{'}$, $b_2^{'}$ and $b_e^{'}$;
- if the resource is sufficient and there is a remainder, allocation of resources b_e to as many data requests as possible;
- if all data requests are allocated resource b_e and there is a remainder, allocation of resources b_2 to as many requests for RT traffic of the second type as possible;
- if there is again a remainder of free resource and there are data requests, allocation of the specified free resource to increase the service speed of these requests.

The use of the described rule $f(s)$ for $v = 33$ and $s = (2, 2, 2)$ is illustrated in Fig. 3. At the first step, it is established that the resource is sufficient to service all requests at minimum speed and there is some residual resource, i.e., $2b_1^{'} + 2b_2^{'} + 2b_e^{'} = 18$ and the residual resource is 15 quanta. The second step involves checking whether a speed increase for data requests is possible, and this possibility is confirmed. Each data request is allocated resource b_e. The residual resource decreases by 8 and now amounts to 7 quanta. At the third step, it is determined that speed increase is possible only for one request of the second type, and the residual resource is insufficient to increase the speed for the second request. Accordingly, the resource of one request of the second type increases to 8 quanta, and the residual resource decreases to 3 quanta. This remaining resource is given for servicing data requests at the fourth step. As a result, the total resource of data requests will be $2b_e + 3 = 19$ speed quanta. For distributing the resource among these requests, known approaches described in [1] can be used, for example, the water-filling algorithm.

It should be noted that the proposed rule is only a particular example. Other rules are considered in some sources, for example in [24].

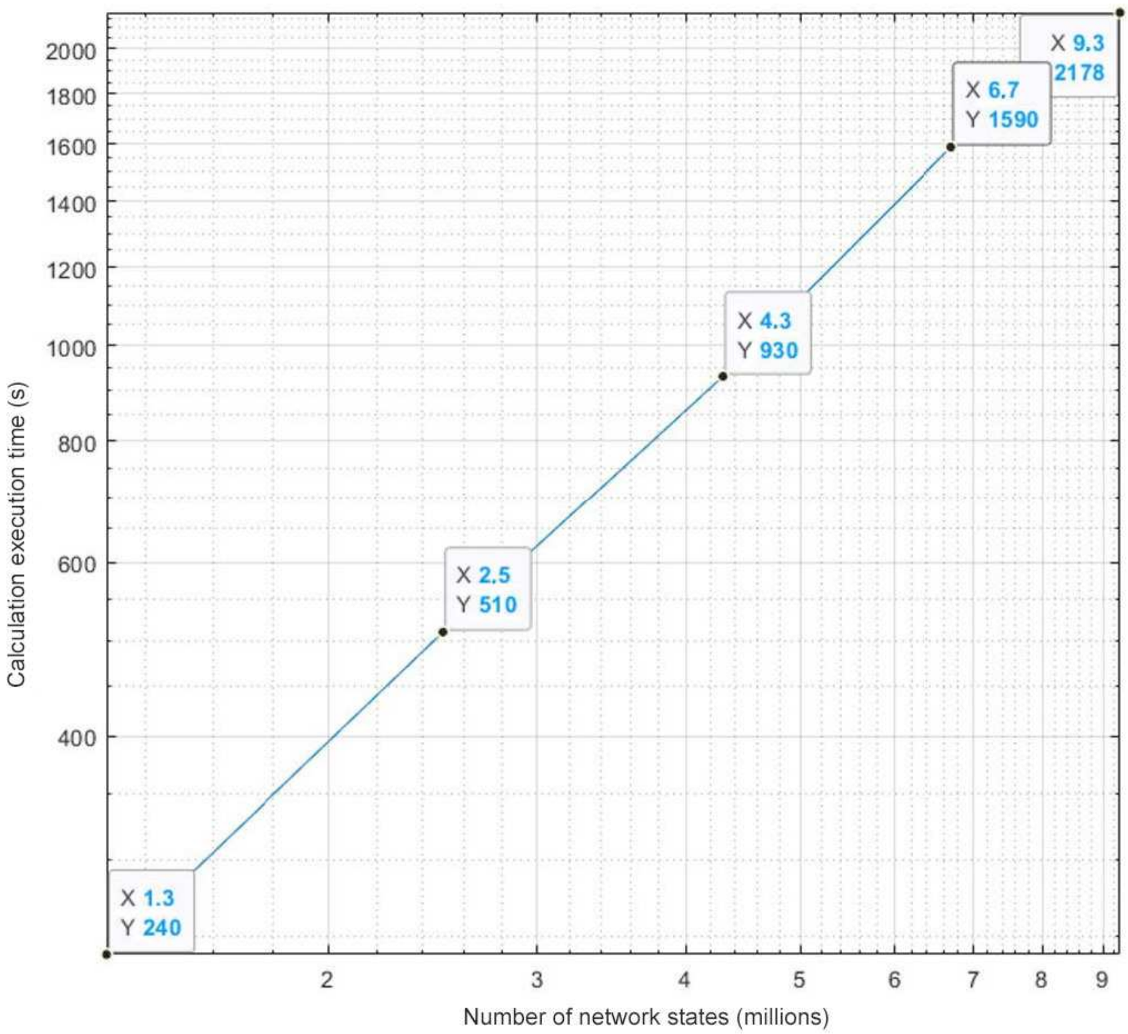

Fig. 4. Dependence of computation time on the number of network states N_{states}.

For the numerical analysis, we developed a MATLAB scenario to form the SEE from a set of network characteristics, solve it using the Gauss-Seidel method, and calculate the quality indicators. An assessment of the possibility of solving SEE of large dimension was carried out, illustrated in Fig. 4.

The dependence of the computation time on the number of states N_{states} is monotonically increasing and nearly linear. For $N_{\text{states}} \approx 9.3$ million, the time was about 36 minutes.

As noted in Section 1, the operator may be interested in both the task of determining the required resource at the network planning stage and the task of assessing the possibility of expanding the subscriber capacity of the network with the available resource.

When solving the first task, dependencies of traffic service quality indicators on the resource are constructed, illustrated in Figs. 5, 6, and 7.

Figure 5 shows that a value P_2 no lower than 0.9 is ensured given a resource of $v \geqslant 96$, while for P_e the required resource is $v \geqslant 88$. For all values of v in the range from 80 to 100, as follows from Fig. 6, the constraint on the maximum fraction of lost requests is satisfied with a large margin. According to Fig. 7, to satisfy the constraint on the average file delivery time, a resource $v \geqslant 87$ is required. Thus, all constraints are satisfied when the network resource $v \geqslant 96$. The minimum required volume of the network resource is 96 speed quanta.

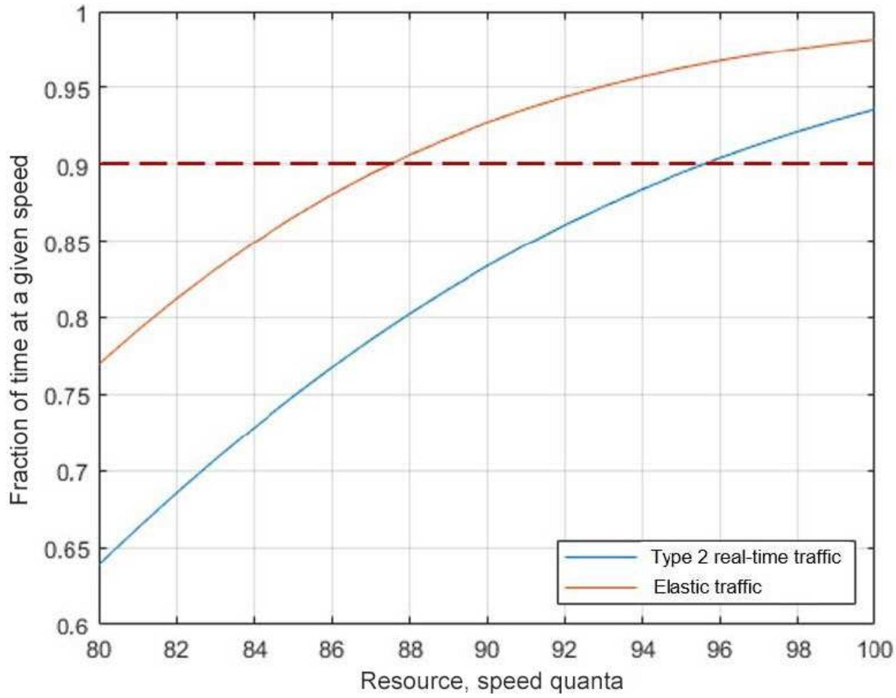

Fig. 5. Dependencies on resource v of the fraction of time P_2 during which RT traffic of the second type is transmitted at the specified high speed, and the fraction of time P_e during which data service traffic is transmitted at a speed not lower than the specified threshold.

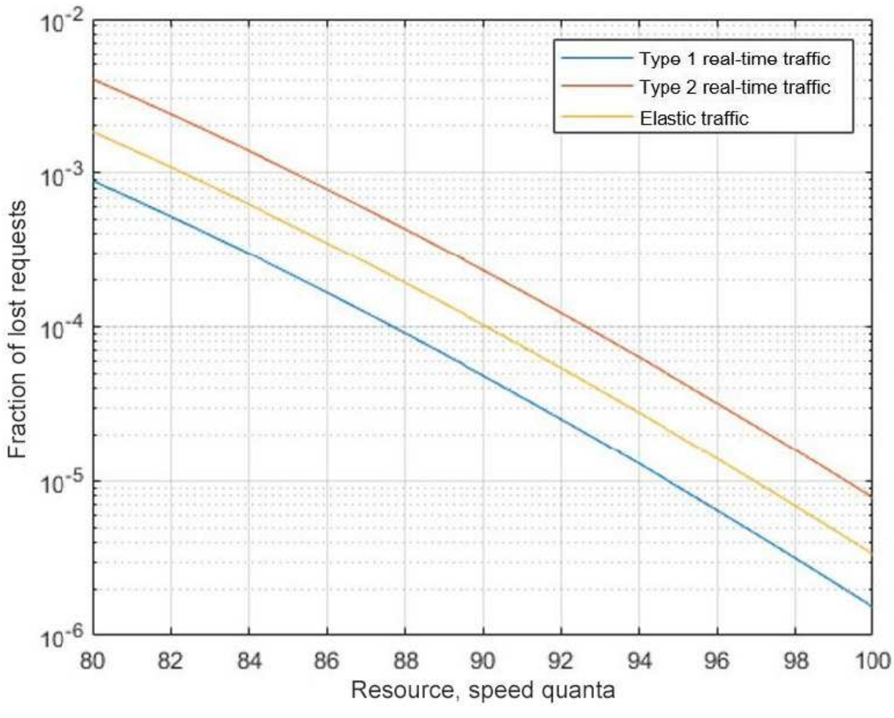

Fig. 6. Dependencies on resource v of the fraction of lost requests of each type due to insufficient resource π_k, $k = 1, 2$ and π_e.

We will assess the possibility of network expansion using the example of increasing the number of consumers of the second RT service. Assume that the network has a resource $v = 100$ and traffic parameters are according to the table with the difference that the possibility of increasing

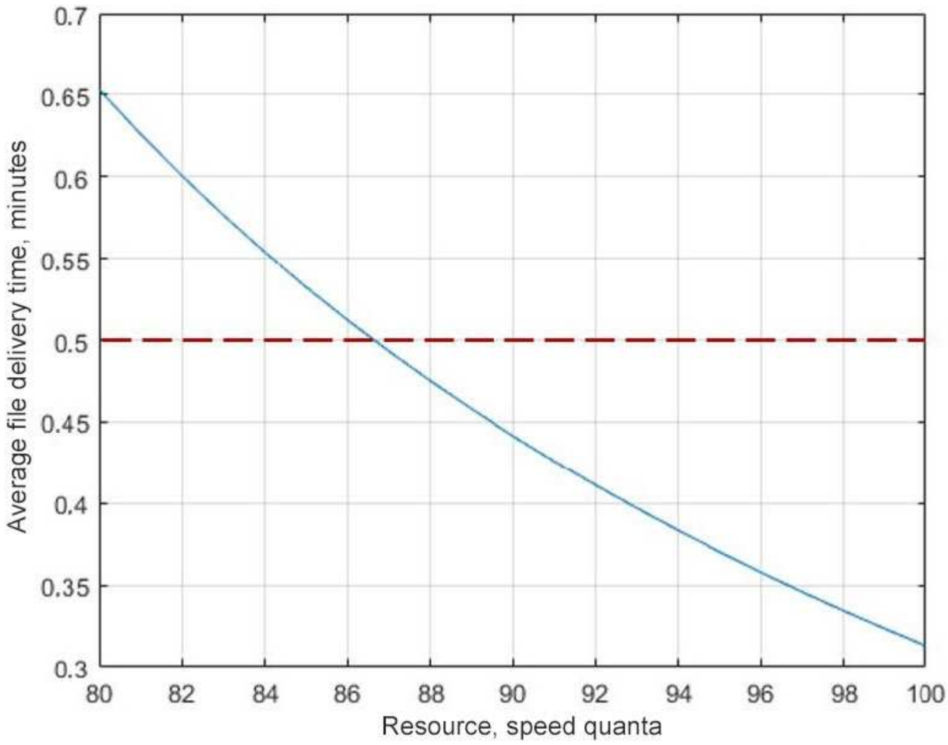

Fig. 7. Dependencies on resource v of the average file delivery time W.

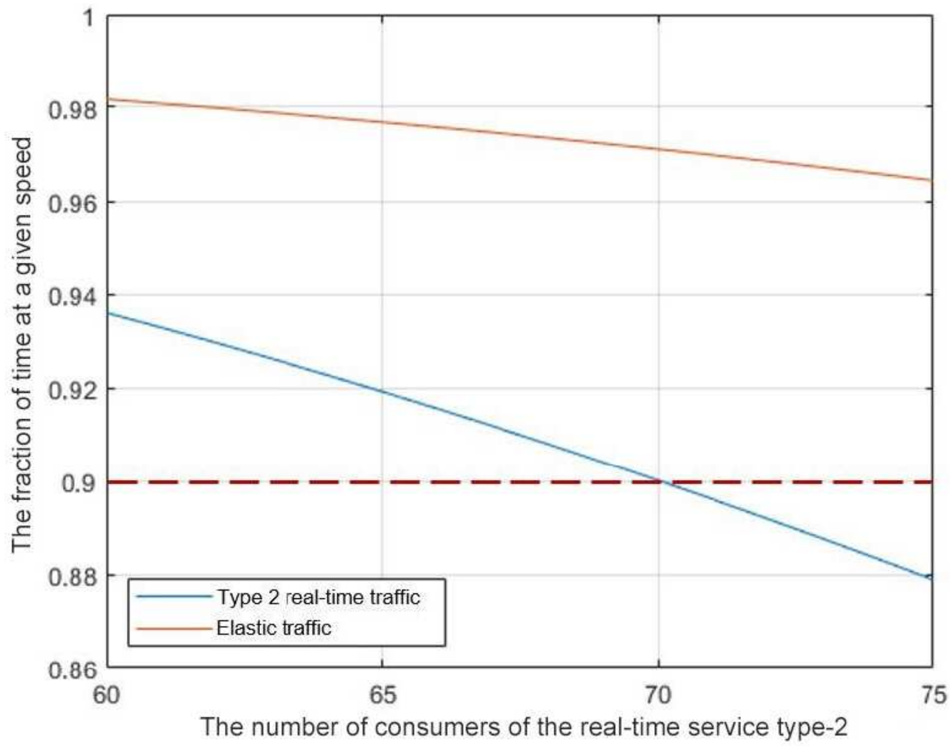

Fig. 8. Dependencies on the number of consumers of the second service N_2 of the fraction of time P_2 during which RT traffic of the second type is transmitted at the specified high speed, and the fraction of time P_e during which data service traffic is transmitted at a speed not lower than the specified threshold.

the parameter N_2 is evaluated and it varies in the range from 60 to 75. The calculation results of indicators P_2 and P_e are presented in Fig. 8. It can be seen that with an increase in N_2, the values of indicators P_2 and P_e decrease. At the same time, the value P_e remains within the specified limits, and for P_2 the constraint is satisfied only for $N_2 \leqslant 70$.

Thus, the network allows an increase in the number of consumers of the second RT service up to 70 without changing the resource volume. If the number of consumers exceeds 70, then to meet the specified constraints on the quality indicators, an increase in the network resource will be required.

5. CONCLUSION

This study builds a model for the joint servicing of real-time and elastic data traffic in a satellite multi-service network access node with a dynamically variable transmission rate. One of the key quality indicators is the fraction of time each service is provided at high speed. The model formalizes the network operation process using the apparatus of multidimensional stepwise Markov processes. Furthermore, relations for calculating QoS indicators have been derived. The software implementation of the model solves the systems of equilibrium equations for the Markov processes using the iterative Gauss-Seidel method. This approach enables the estimation of performance indicators for large-scale networks, a capability confirmed by numerical experiments involving up to ten million network states. Examples are provided to demonstrate the model's application in solving two key problems: 1) determining the required resource during the network planning stage, and 2) assessing the potential for expanding the network's subscriber capacity given the available resources. The model is suitable for integration into software for satellite network management systems. Furthermore, it can be used in operational contexts to justify the feasibility of measures aimed at enhancing network characteristics and modernization.

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