Estimation of time characteristics of systems with network topology and stochastic processes of functioning

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Abstract. The article describes the proposed approach to modeling stochastic processes of the boundary layer of complex systems with a network topology, based on the methods of queuing theory. Based on the developed models, algorithms for calculating the estimates of the main temporal characteristics of the functioning quality of the analyzed processes are built. To test the proposed models, methods and algorithms, a structure has been developed and a computational experiment has been conducted to assess the quality of service requirements in telecommunications networks of the NGN concept, which are a typical modern example of complex systems with network topology and stochastic processes of operation (data flow service).

1. Introduction

To simulate heterogeneous processes in various subject areas such as the organization of transportation, the provision of various services, diffusion in the chemical industry, and the transmission of information in the telecommunications sphere, stochastic systems with network topology are used. Such systems are complex both in terms of the composition of elements and their interaction, and in terms of the presence of a large number of uncertainty factors describing objects and functioning processes. The network nature of the systems is reflected in the presence of communications located in a certain space, including paths, channels, lines, special network devices. The processes occurring in these systems can be divided into two groups: the processes of interaction with the external environment and the processes of internal interaction. In accordance with the division of processes into two groups, the boundary layer and the core are distinguished in the systems. The typical processes of the boundary layer include the following processes: obtaining resources (information flows) from the external environment, processing resources (information flows), classifying resources and generating information for further processing steps and sending it to the system core and / or the external environment. The main processes of the core system are associated with the transfer (transportation) of information. Among the processes of the core and the boundary layer there are processes functioning in a random mode, this explains the stochastic nature of the systems under consideration.

A generalized description of the structural components and processes of complex stochastic systems with a network topology is given in table 1.

A typical model of the architecture of modern complex stochastic systems can be represented as a combination of four planes: the plane of providing intellectual services (administration, resource management) and the implementation of operational management, the plane of program management (interaction algorithms of structural elements of the system), the plane of switching and transportation and the...
plane of access and data (the relationship of the system with the external environment, receiving and adapting information from the external environment) [1].

| Structural element / process | Description |
|-----------------------------|-------------|
| Boundary layer system       | Many elements of the system that have connections with the external environment and the elements of the system core |
| Core system                 | Many interrelated elements of the system that have no connection with the external environment |
| System devices              | Hardware to keep the system running |
| User                        | The person working with the system |
| Data                        | Information or resource converted to the format required for transmission and processing in the system |
| Data stream                 | A set of data, combined according to some principle for processing in the system |
| Data block                  | The part of the data considered as a whole from the standpoint of processing |
| Data packet                 | A data block provided with service information for processing in the system |
| Requirement (message)       | Data block having a service request |
| Package formation           | The set of processes for creating a data packet: classification, division into blocks, the formation of service information |
| Data service                | The set of processes for receiving, processing and further transmission of data |
| Traffic                     | Network traffic |

As a basic example of a complex system with a network topology, demonstrated in this article, we consider the latest telecommunications concept systems (NGN) of the last generation. The structural representation of the telecommunications systems of the NGN concept is shown in figure 1 [2].

Managing complex stochastic systems with a network topology is associated with solving a whole range of tasks: regulating the policy of providing information transmission media, resources, organizing communication sessions, providing security, etc. The time characteristics of the processes occurring in the system are among the most important indicators of the efficiency and quality of functioning of the systems under consideration. Obtaining estimates of the temporal characteristics of the functioning of processes requires the development of special tools that take into account the structure of the systems under study and the stochastic nature of the processes. Of interest are tools that allow not only to obtain estimates, but also to develop feasible, constructive strategies to optimize the management of improvements. A well-tested area for developing such tools is mathematical modeling. The study of methods of mathematical modeling aimed at obtaining estimates of the temporal characteristics of the functioning of processes in complex stochastic systems with network topology, the work of V M Vishnevsky, V G Ushakov, N N Moiseev, B S Tsybakov and other scientists [3] – [5].

The results of the work presented in this article are aimed at the construction of mathematical models, methods and algorithms for estimating the temporal characteristics of the efficiency of the processes of the boundary layer of complex stochastic systems with network topology. The article describes a computational experiment that demonstrates approbation of the proposed tools for assessing the quality of service applications in the boundary layer of telecommunications systems of the latest generation.
2. Mathematical modeling of boundary layer processes of complex stochastic systems with network topology

The processes of the boundary layer are associated with obtaining resources from the external environment, their processing and transfer to the kernel, as well as obtaining resources from the kernel, their processing and sending them to the external environment. One of the mechanisms for improving the performance of processes in the boundary layer is the differentiation of flows according to service requirements. This is achieved through the formation of new flows, in which resources are aggregated by priority of service.

If we consider modern telecommunication systems as an example, then, in accordance with the concept of NGN (the next generation network), resource flows (traffic) are heterogeneous, they are serviced on the basis of service priorities. The main indicator for evaluating the efficiency and quality of functioning of these systems is the delay time of requirements, which is the sum of the following components: queue waiting time and service time at the boundary layer node, waiting time and service at the network core and network transport time [6], [7]. Technological and methodological support of networks with the concept of NGN makes it possible to effectively estimate the waiting time of the queue and service in the network core, as well as the transport time over the network. Less developed and standardized is the technology for estimating the time the requirement is in the boundary layer; there is no uniform methodology for conducting assessment procedures in this area. The article proposes an approach to estimating the residence time of the requirements of different priorities in the system, based on the theory of mass service.

To simulate the processes of functioning of the boundary layer, we represent it as a set of components (network nodes), each of which is considered as a queuing system (QS) with a multi-priority service. The number of service priorities in the node will be equal to 8 (according to the IP
protocol used in NGN networks). It is assumed that: the flow of requirements (resources) in such a network can be described as simplest with intensities \( \lambda_j, \ i = 1,8 \) (according to the number of priorities), the service requirements of all priorities are distributed according to the exponential law with intensities \( \mu_i, \ i = 1,8 \) [1].

The functioning of the systems under consideration is accompanied by a change of states described by the characteristics of the queue and service. When a flow enters the system, the requirements are distributed in queues according to the priority of service. Service at each node of the network is based on priorities. In this case, the requirements of a higher priority are ahead in servicing the requirements of a lower priority, regardless of the time of arrival at the node. The main characteristics of the description of the processes are, respectively, the time spent in the queue requirements and service time. For the described system, there is such a concept as the “life” time, which characterizes the behavior of requests in the service queue [4], [5], [8], [9]. The residence time of requests in the queue before the expiration of the “life” time is considered a random variable distributed according to the exponential law with parameters \( \omega_j, \ i = 1,8 \). The transition of the system from one state to another is carried out randomly and, according to queuing theory, is described using a transition probability matrix.

Given that each QS serves the flow of requirements of all 8 priorities, we will consider its state as an ordered set of variables \( (k_0, k_1, \ldots, k_8) \), where \( k_0 \) – priority of the requirement that is being serviced at the time in question, \( k_i \) – the number of requests in the \( i \)-th priority queue. With the fulfillment of the above assumptions, the process of servicing requirements in the system under consideration can be described as a Markovian random process of birth and death. The Kolmogorov equation for the systems described by the Markov process of birth and death allows to obtain the values of the probabilities of being in any of the system states, on the basis of which it is possible to calculate the temporal characteristics of the system [3], [10].

As part of the work for the considered service processes, the following system of differential equations was obtained:

\[
\frac{dP_{(0,0,0,0,0,0,0,0,0)}(t)}{dt} = -P_{(0,0,0,0,0,0,0,0,0)}(t)\sum_{j=1}^{n} \lambda_j - \sum_{k_0=1}^{n} P_{(k_0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j); \\
\frac{dP_{(k_0,0,0,0,0,0,0,0,0)}(t)}{dt} = -P_{(k_0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j)P_{(k_0,1,0,0,0,0,0,0,0)}(t)\omega_1 + P_{(k_0,0,1,0,0,0,0,0,0)}(t)\omega_2 + \\
+ P_{(k_0,0,0,0,1,0,0,0,0)}(t)\omega_3 + P_{(k_0,0,0,0,1,0,0,0,0)}(t)\omega_4 + P_{(k_0,0,0,0,0,1,0,0,0)}(t)\omega_5 + \\
+ P_{(k_0,0,0,0,0,0,1,0,0)}(t)\omega_6 + P_{(k_0,0,0,0,0,0,0,1,0)}(t)\omega_7 + P_{(k_0,0,0,0,0,0,0,0,1)}(t)\omega_8; \\
\frac{dP_{(k_0,k_1\ldots,k_8)}(t)}{dt} = -P_{(k_0,k_1\ldots,k_8)}(t)(\mu_{k_0} + \sum_{j=1}^{n} k_j \omega_j) + +P_{(k_0,k_1\ldots,k_8)}(t)\lambda_1 + P_{(k_0,k_1\ldots,k_8)}(t)\lambda_2 + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)\lambda_3 + P_{(k_0,k_1\ldots,k_8)}(t)\lambda_4 + P_{(k_0,k_1\ldots,k_8)}(t)\lambda_5 + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)\lambda_6 + P_{(k_0,k_1\ldots,k_8)}(t)\lambda_7 + P_{(k_0,k_1\ldots,k_8)}(t)\lambda_8 + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)(k_1 \omega_1 + \mu_{k_0}) + P_{(k_0,k_1\ldots,k_8)}(t)(k_2 \omega_2 + \omega_2) + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)(k_3 \omega_3 + \omega_3) + P_{(k_0,k_1\ldots,k_8)}(t)(k_4 \omega_4 + \omega_4) + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)(k_5 \omega_5 + \omega_5) + P_{(k_0,k_1\ldots,k_8)}(t)(k_6 \omega_6 + \omega_6) + \\
+ P_{(k_0,k_1\ldots,k_8)}(t)(k_7 \omega_7 + \omega_7) + P_{(k_0,k_1\ldots,k_8)}(t)(k_8 \omega_8 + \omega_8) + \\
+ \cdots + P_{(k_0,k_1\ldots,k_8)}(t)(k_8 \omega_8 + \omega_8) \tag{1}
\]

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\[ + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(k_0\omega_1 + \omega_3) + P_{(k_0,k_1,...,k_{j+1},k_j)}(t)(k_0\omega_1 + \omega_6) + \]
\[ + P_{(k_0,k_1,...,k_{j+1},k_j)}(t)(k_0\omega_1 + \omega_3) + P_{(k_0,k_1,...,k_j)}(t)(k_0\omega_1 + \omega_6), \quad 1 \leq k_j < K_j, \quad j = 1, \ldots 8 \]
\[ \frac{dP_{(k_0,k_1,...,k_j)}(t)}{dt} = -P_{(k_0,k_1,...,k_j)}(t)(\mu_{k_0} + \sum_{j=1}^{n} k_j\omega_j) + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_1 + \]
\[ + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_2 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_3 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_4 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_5 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_6 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_7 + P_{(k_0,k_1,...,k_{j-1},k_j)}(t)(\lambda_8, \quad k_j = K_j, \quad n = 8, \]
\[ \sum_{k_0,...,k_j} P_{(k_0,k_1,...,k_j,...,k_n)}(t) = 1, \quad 0 \leq P_{(k_0,k_1,...,k_j,...,k_n)}(t) < 1, \]

where \( P_{(k_0,k_1,...,k_j,...,k_n)} \) – the probability of the system being in a state \((k_0,k_1,...,k_n)\) at the moment \( t \) after the start of operation the system \([11],\ [12]\). For the initial moment of time \( t = 0 \) we make the assumption that: \( P_{(0,0,0,0,0,0,0,0,0)}(0) = 1, \quad P_{(k_0,k_1,...,k_n)}(0) = 0, \quad 1 \leq k_j < K_j, \quad j = 1, \ldots 8 \),

where \( K_j \) – maximum number of requests in the \( j \)–th queue.

To describe the stationary mode of operation of the QS, the system of differential equations (1) can be transformed into a system of linear equations (2):

\[ 0 = -P_{(0,0,0,0,0,0,0,0,0)}(t) \sum_{j=1}^{n} \lambda_j - \sum_{k_0=1}^{n} P_{(k_0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j), \]
\[ 0 = -P_{(k_0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,1,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,1,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,1,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,1,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,1,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]

\[ 0 = -P_{(k_0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,0,0)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P_{(k_0,0,0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + P_{(k_0,0,0,0,0,0,0,0,0,0,0,0,0,1)}(t)(\mu_{k_0} + \sum_{j=1}^{n} \lambda_j) + \]
\[ + P(k_0, k_1, \ldots, k_8) \lambda_3 + P(k_0, k_1, \ldots, k_4) \lambda_4 + P(k_0, k_1, \ldots, k_5) \lambda_5 + \\
+ P(k_0, k_1, \ldots, k_6) \lambda_6 + P(k_0, k_1, \ldots, k_7) \lambda_7 + P(k_0, k_1, \ldots, k_8) \lambda_8, \]
\[ \sum_{k_0, k_1, \ldots, k_8} P(k_0, k_1, \ldots, k_8) = 1, \quad 0 \leq P(k_0, k_1, \ldots, k_8) < 1, \]

where \( P(k_0, k_1, \ldots, k_8) \) - probabilities of the system being in stationary mode of operation \((k_0, k_1, \ldots, k_8), 1 \leq k_j < K_j, j = 1 \ldots 8, n = 8\). The solution of this system of linear equations is the probabilities of the states of the system \( P(k_0, k_1, \ldots, k_8) \) [11], [12]. As mentioned earlier, these probabilities can be used to calculate the temporal characteristics of the functioning of the system, in particular, one of the most important characteristics for assessing the effectiveness and quality of service of the system - the delay time requirements in the boundary layer.

3. Algorithm for calculating the temporal characteristics of boundary layer processes of complex stochastic systems with network topology

The proposed algorithm is based on the imitation of the process of arrival, departure and maintenance of requirements in the boundary layer node. Due to the stochastic nature of the flows, the algorithm provides for finding the average value of the delay of requirements. In addition, for each priority (queue), this value is calculated separately. Moreover, the calculation of the delay value is made taking into account that the system is in a stationary state. Thus, if the requirement of \( i \) - th priority comes into the system, the system can be in one of the states \((k_0, k_1, \ldots, k_8)\). Its maintenance can begin only after all the requirements of \( i \) - \( i+1 \) queues and \( i \) queue have been serviced. Accordingly, due to the priority of service, the state of the \( i \) - th queue, the state of higher priority queues, and the state of the service process affect the value of the time spent in the queue. Therefore, the average delay value is found for each combination \((k_0, k_1, \ldots, k_i)\), characterized by the probability:

\[ P(k_0, k_1, \ldots, k_i) = \sum_{k_0, k_1, \ldots, k_i} P(k_0, k_1, \ldots, k_8) \]

The average delay time for the \( i \) - th priority requirement is calculated by the formula \( T_{deli} = \sum_{k_0, k_1, \ldots, k_i} T_{k_0, \ldots, k_i} \), where \( T_{k_0, \ldots, k_i} \) - average delay time for combination \((k_0, k_1, \ldots, k_i)\).

Thus, the algorithm simulates the process of the arrival and departure of requests in queues of higher than the \( i \) - th priority and calculates the average delay time \( T_{k_0, \ldots, k_i} \) (see the figure 2) [12], [13]. It should be noted that due to the fact that the arrival of new requirements does not affect the servicing of the requirements of the first priority queue, the time is calculated using the formula: \( T_{deli} = T_{serv} + k_1 \times T_1 \), where \( T_{serv} \) - determines the service time of the request of the \( k_0 \) - th already in the system, \( T_1 = \frac{1}{\mu_1} \) - service time requirements of the first type, \( k_1 \) - the number of requests in the queue of the first type. The calculation of the delay time in queues lower than the first priority is carried out using the process of imitation of the arrival and departure of requirements. The algorithm takes into account that during maintenance of the \( k_0 \) - th requirements in the system can come

\[ g_j = \frac{\lambda_j}{\mu_0} \]

and leave \( r_j = \frac{\alpha_j}{\mu_0} \) requirements of the \( j \) - th type, while the number of requirements left the system can not exceed the number of requirements standing in the \( j \) - th queue. This is reflected in a formula that describes changes in the system over time \( t \):
\[ k'_j = k_j - \min(k_j, r_j) + g_j \]  \hspace{1cm} (4)

The residence time of requests in the \( i \)-th queue with fixed values \( k_0, k_1, \ldots, k_i \) is calculated by the formula:

\[ T_{k_0, \ldots, k_i} = Td \cdot P_{k_0, \ldots, k_i}, \text{ where } Td = 1 \cdot \frac{1}{\mu_0} + k_1 \cdot \frac{1}{\mu_1} + \ldots + k_i \cdot \frac{1}{\mu_k}. \]  \hspace{1cm} (5)

The described algorithm allows to calculate the average delay time of requests in the boundary layer for the requirements of each priority and carry out a parametric analysis of the change in delay times when changing such parameters as \( \lambda_i \) — demand flow rate \( \mu_i \), service intensity requirements of the network node, \( \omega_i \) — flow rate of care requirements after a lifetime [12], [13], [14].

![Diagram](image)

**Figure 2.** Algorithm for calculating the delay time requirements for all priority queues.

4. **Computational experiment**

The computational experiment is implemented on the basis of the algorithm proposed above. It carried out a parametric analysis of the effect on the average delay time of requests in the queue of the size of requests of threads of different priorities and component load levels. The telecommunications network of the NGN concept was chosen as the object of study, one of the boundary layer components was considered. The main processes of its operation: incoming flows of requests come from both...
individual users of the system and service servers. When entering a component, the requirements are distributed to the queues in accordance with the priority of service. Each requirement is characterized by a size (MTU), which determines the intensity of its service in the component. The intensity of withdrawal of requirements from a component is limited by the maximum transmission rate of packets through a single component device, depending on the MTU size (in the calculations for a single device), or throughput of the communication line (in the calculations for the system component as a whole). System load is defined as the ratio of the intensities of the incoming and outgoing flows of requirements in a component. The number of priorities (queues) is three. Dependencies are obtained for the requirements of the first and second priorities. According to the concept of NGN, it is in these queues that the traffic that is most critical to the delay time is transmitted [9], [13]. The results of the experiment are presented in figures 3 – 4.

![Diagram](image)

**Figure 3.** The delay time of the first-priority requests depending on the size of the first and second priority MTUs (system load up to 10%).
Figure 4. The delay time of the first-priority requests, depending on the size of the first and second type MTUs (system load over 10%).

Parametric analysis showed that:

1) the influence of the size of the requirements of any of the priorities takes place for the delay time of all priorities, and it becomes noticeable when the system component is loaded over 10%;

2) the minimum delay time when the system is loaded up to 10% is observed when choosing the sizes of the first, second and third priority requirements, respectively, 536 – 536 – 1500 (bytes), for loading the system over 10%, respectively 46 – 46 – 1500 (bytes);

3) resizing the requirements of the first stage when the system is loaded up to 10% allows reducing the delay time for the first priority requirements within 20%;

4) when the system is loaded over 10%, varying the size of the first-priority requests allows reducing the delay value of the first-priority requests up to 45%.

The results of the study allow us to make recommendations on the selection of optimal values for the size of data packets in order to be able to regulate the service time of flows in the network [13], [15]. In turn, this allows you to improve the quality of service of traffic in the NGN concept networks.

5. Conclusion

The proposed algorithm for estimating the temporal characteristics of complex systems is based on the construction of a stochastic model describing the individual components of the system. The algorithm for finding the temporal characteristics is imitative, it simulates the process of receiving, waiting and servicing requirements in the system. The calculation of the delay time of requirements in the system, carried out using the developed algorithm, allows: to carry out a parametric analysis of the influence of individual system parameters on the system’s time characteristics, to select the system parameters that ensure the optimum mode of operation, to evaluate the quality of functioning of the existing system.

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