The object of research is Markov models of network nodes with UDP (User Datagram Protocol) and TCP (Transmission Control Protocol) traffic and their differences.

The task solved is the lack of Markov models of network nodes describing the behavior of TCP traffic from the point of view of packet retransmissions and packet delivery guarantees.

Markov models of network nodes describing traffic behavior with guaranteed packet delivery have been further advanced. Given the comparison of the models, the differences from the classic models serving TCP traffic were shown, for each packet flow, an additional dimensionally was added to the graph of states and transitions, which takes into account the retransmission of a lost packet. The comparison graph shows similar behavior of queue length and packet loss for both types of traffic. But the nature of the curves is different. With TCP traffic, packet loss can exceed 5 percent. In addition, lost packets must be retransmitted, which increases the load on the network node.

More failures and packet queue lengths at a network node during peak load typically occur with TCP traffic compared to UDP traffic. At peak load, the difference in service failures can reach 20–30 percent. The main reason is that TCP uses flow control and rate-limiting mechanisms to avoid network congestion and ensure efficient data transfer between nodes.

The Markov model of TCP traffic requires an additional dimensionally on the graph of states and transitions, which affects the behavior of queues and packet failures.

The investigated problem was solved due to the universality and diversity of the mathematical apparatus of Markov mass service systems.

The results could be used in network modeling software products for building and reengineering the topology of electronic communications networks at enterprises and organizations

Keywords: Markov model, network traffic, network node, mass service system

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ASSESSMENT OF QOS INDICATORS OF A NETWORK WITH UDP AND TCP TRAFFIC UNDER A NODE PEAK LOAD MODE

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1. Introduction

There is a huge increase in the amount of data transmitted over electronic communications networks. With this growth comes the need to efficiently transfer, process, and store this data. With the development of various services, such as video streaming, virtual reality, cloud services, and the Internet of Things, the volume of traffic on the network becomes significantly higher. Optimizing network resources makes it possible to better cope with this growth. Optimization makes it possible to maximize the use of available resources, reduces costs, and increases network performance. This is especially important in business environments where resource efficiency directly affects profitability. Managing the resources of network nodes is necessary to ensure the quality of service (QoS), which allows maintaining a high level of service quality, especially under conditions when a large number of users compete for access to limited resources. The issue of reducing energy consumption by network devices and reducing the energy footprint has become increasingly important in the modern world. Therefore, taking into account the above, it is possible to assert the relevance of optimization of network resources.

2. Literature review and problem statement

The mass service system (MSS) mathematical apparatus is the most common mathematical apparatus used to model electronic communication networks. A classic work in the field of MSS theory is [1]; it was aimed at the development and implementation of innovative methods of management and optimization of business processes.

Nowadays, Markov models of MSS are an integral part of the theory of tele-traffic and have been developed due to the expansion of the range of problems of electronic communications and networks. Modern general issues of stochastic process modeling are discussed in [2]; it contains an introduction to the theory of stochastic processes, including mass service Markov systems (MSMS), provides a clear understanding of the main concepts and methods of analysis of such systems, but it is purely theoretical and does not provide enough examples for understanding real situations of application in electronic communications.

Paper [3] provides an overview of the latest achievements in the theory of Markov models of mass service systems (MSS), new models of mass service systems, methods of their analysis and optimization are considered here, and a general idea of new results in the field is given. But, in turn, a detailed description of the new results is not given and there are no practical examples of the application of the proposed models.

Study [4] considers Markov models of MSS with failures. Here, different types of MSS models with failures, their properties and methods of analysis are considered, and a thorough understanding of the theory of MSS with failures is given. But the authors do not give practical examples of the application of MSS models with failures.

Paper [5] discusses different types of MSS models with server-dependent arrivals, their properties and analysis methods, and gives an overview of the new results, but does not provide a detailed description of the new results.

In [6], a thorough introduction to the stochastic modeling methods used for the analysis of MSS is given. Stochastic modeling methods, their advantages and disadvantages are considered, a thorough understanding of stochastic modeling methods is given.

Paper [7] focuses on the application of queuing theory, in particular Markov models, to the design and evaluation of computer systems, it describes many additional mathematical concepts, but does not consider real network protocols.

Work [8] covers a wide range of topics on stochastic processes, including Markov models for mass service systems, but it is not sufficiently detailed in some aspects of the application of models in electronic communications.

In [9], Markov models of MSS with restrictions on the length of queues were considered, but no approximation was made to take network protocols into account.

In [10], modern problems and methods of queuing theory are described, modern achievements in the field are discussed, but the non-ordinary nature of traffic and multi-flow systems is not taken into account.

Thus, it is shown that the mathematical apparatus of Markov models is convenient enough to describe the process of packet transmission in network nodes, but the existing models describe only traffic with non-guaranteed delivery. Then there is the problem of the lack of a description of traffic with guaranteed delivery by means of the mathematical apparatus of Markov models.

3. The aim and objectives of the study

The purpose of our study is to evaluate quality of service (QoS) indicators in network nodes during peak load, taking into account certain differences between UDP and TCP protocols. This will make it possible to widely use the resulting UDP and TCP traffic models in network design and optimization where they could be used to analyze and simulate the behavior of TCP connections. These models make it possible to effectively study the interaction of traffic in the network, predict the load, optimize resources, and improve the quality of service (QoS). They are also useful for analyzing network protocols, designing routing strategies, and predicting possible failures and network recovery. All of this contributes to improving the performance, efficiency, and reliability of the network environment in various areas, including business, telecommunications, and information technology.

To achieve the goal, the following tasks were set:

– to build a model of a network node serving UDP traffic, calculate probabilities of the states of such a system;

– to build a Markov model of a network node serving TCP traffic, calculate probabilities of the states of such a system;

– to compare the resulting models and calculation results.

4. The study materials and methods

The object of research is Markov models of network nodes with UDP and TCP traffic.

Research hypothesis assumes that Markov models could be effectively used to describe and predict the behavior of network nodes and show the difference in the functioning of network nodes from the point of view of UDP and TCP packet transmission.

Accepted assumptions: stationarity of traffic, ergodicity of the graph of states and transitions of the Markov chain, lack of correlation in stochastic traffic indicators.

Simplification: ideal communication channels, packets come from the outside from an unknown source and go nowhere after being serviced, the information carried by the packets is not considered, the priorities of the packets are not considered.

Hardware: personal computer.

Software: calculations were performed in Mathcad 14.

TCP and UDP are two different transport layer protocols in the network architecture. The main difference lies in the approaches to data transmission: TCP provides reliable and consistent data delivery over an established connection with flow control mechanisms and confirmation of successful packet delivery. UDP provides a connectionless, unreliable transmission method without additional checks and delivery status messages.

It is obvious that mathematical differences in Markov models of network nodes for TCP and UDP traffic may arise due to different characteristics of these protocols. Some key aspects that affect the mathematical representation of Markov models include:

– in the case of TCP, there can be more states, because there is a mechanism for establishing and maintaining a connection. There may be additional states associated with various stages of the connection life cycle (establishment, data transfer, closing);

– the mathematical notation of state transition probabilities may differ for TCP and UDP. For example, the connection success and closing probabilities for TCP can affect the overall performance of a node;

– consideration of time delays and timeouts in Markov models can be important for TCP as it enables reliable data transmission with a connection;

– Markov models for TCP may include consideration of packet loss probabilities and retransmission mechanisms.

5. Results of the research on forecasting the state of the package service system

5. 1. Markov model of a network node serving two flows of User Datagram Protocol packets

The network node receives traffic with non-guaranteed delivery, which consists of the superposition of two Poisson flows with intensities λ_1 and λ_2, respectively. It is known that the packet service intensity of these flows is equal to μ_1 and μ_2, respectively. Node memory is divided between thread queues. The maximum number of packets n_1 and n_2 that they can hold is calculated for the queues of each flow. Let's introduce the set of possible states of the modeled network node. Let E_{ik} be the state of a network node, which corresponds to the situation when there are *i* packets of the first flow and *k* packets of the second flow in the system. The graph of states and transitions of such a system is shown in Fig. 1.

To solve the problem set, a decomposition approach is used – the initial problem of a large dimensionally is divided into stages, at which each time a problem of a smaller dimensionally is solved. In this case, it is suggested to group the layers of states, for example, in rows (Fig. 2). Then the grouped states E_{Ri} contain in the middle the real states of the system $\{E_{i0},E_{i1},E_{i2},...,E_{in2},\}$, where *i* is the line number.

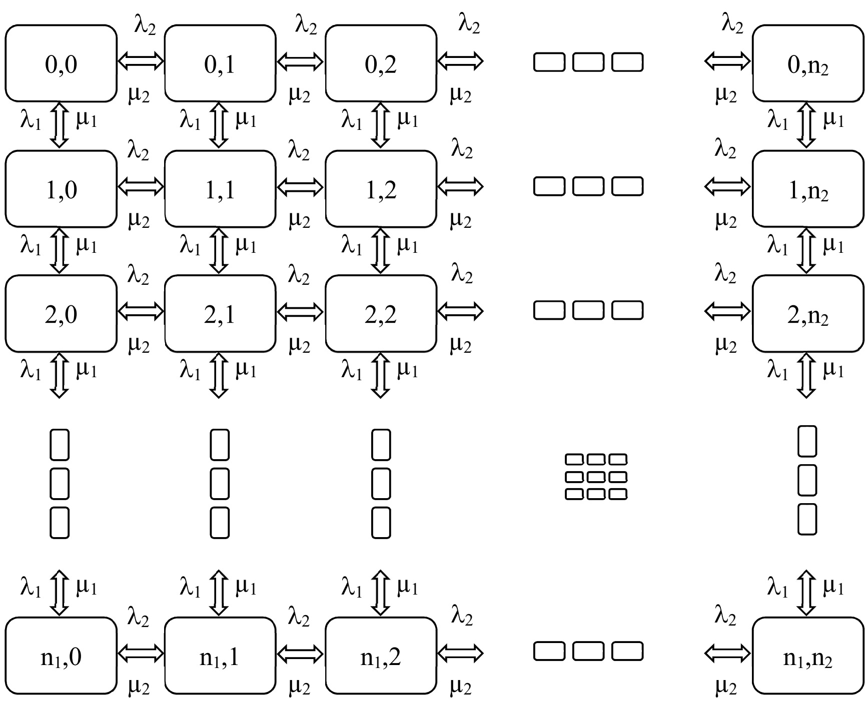

Fig. 1. A graph of states and transitions of a system with two streams of packets in a network node

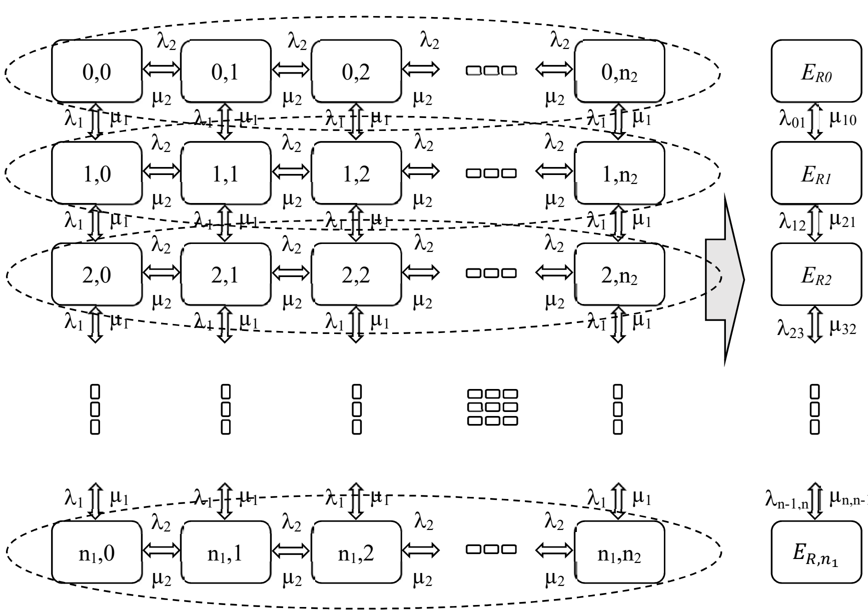

Fig. 2. Reducing the dimensionality of the system by grouping states into series

For the resulting graph of states and transitions, the dimensionality of which is smaller than the original one, the intensities of transitions from layer *i* to *i*+1 were calculated:

$$\lambda_{i,i+1}=\sum_{k=0}^{n_2}\lambda_1\widehat{P}_{ik}=\lambda_1\sum_{k=0}^{n_2}\widehat{P}_{ik}, \tag{1}$$

where $i=0,1,...,n_1-1$.

$\widehat{P}_{ik}$ is the conditional probability of the system being in the *k*-th state of the *i*-th layer, provided that it is in this layer.

Since $\sum_{k=0}^{n_2}\widehat{P}_{ik}=1$, according to (1), $\lambda_{1,i+1}=\lambda_1$, $i=0,1,...,n_1-1$.

The intensity of the transition from the state $E_{R,i+1}$ to E_{Ri} was also found:

$$\mu_{i+1,i}=\sum_{k=0}^{n_2}\mu_1\widehat{P}_{i+1,k}= =\mu_1\sum_{k=0}^{n_2}\widehat{P}_{i+1,k}=\mu_1, \tag{2}$$

where $i=0,1,...,n_1-1$.

Thus, the intensities of transitions between group states have been obtained, and now we shall find the distribution of probabilities of the system being in each of the layers. Taking into account ratios (1), (2), the graph of states and transitions takes the form shown in Fig. 3.

To find the probabilities P_i, $i=1...n_1$ of the system being in layer *i*, the balance equation for the system with grouped states is written:

$$\begin{cases}\mu_1P_1-\lambda_1P_0=0,\\ \lambda_1P_0+\mu_1P_2-(\lambda_1+\mu_1)P_1=0,\\ \dots\dots\dots\dots\\ \lambda_1P_{i-1}+\mu_1P_{i+1}-(\lambda_1+\mu_1)P_i=0,\\ \dots\dots\dots\dots\\ \lambda_1P_{n_1-1}-\mu_1P_{n_1}=0.\end{cases} \tag{3}$$

To simplify the form of relation (3), the substitution $z_i=\lambda_1P_{i-1}-\mu_1P_1$ [9, 10] was made, and relation (4) was obtained:

$$\begin{cases}z_1=0,\\ z_1-z_2=0,\\ \dots\dots\\ z_i-z_{i+1}=0,\\ z_{n_1}=0.\end{cases} \tag{4}$$

Hence $z_1=z_2=...=z_{n1}=0$, that is:

$$\lambda_1P_{i-1}+\mu_1P_i=0, \tag{5}$$

where $i=1,2,...,n_1$.

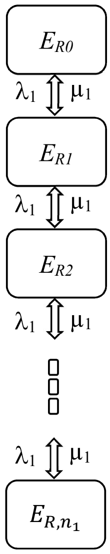

Fig. 3. Graph of states and transitions of a system with grouped states

In this case:

$$P_i = \frac{\lambda_1}{\mu_1} P_{i-1}, \qquad (6)$$

where $i=1,2,\ldots,n_1$.

Then:

$$P_1 = \frac{\lambda_1}{\mu_1} P_0,$$

$$P_2 = \frac{\lambda_1}{\mu_1} P_1 = \left(\frac{\lambda_1}{\mu_1}\right)^2 P_0,$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (7)$$

$$P_i = \left(\frac{\lambda_1}{\mu_1}\right)^i P_0,$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$P_n = \left(\frac{\lambda_1}{\mu_1}\right)^n P_0.$$

The value of P_0, which corresponds to the absence of packets in the network node, is found from the normalization condition:

$$\sum_{i=0}^{n} P_i = P_0 \sum_{i=0}^{n_1} \left(\frac{\lambda_1}{\mu_1}\right)^i = 1. \qquad (8)$$

Hence:

$$P_0 = \frac{1}{\sum_{i=0}^{n_1} \left(\frac{\lambda_1}{\mu_1}\right)^i}. \qquad (9)$$

Then:

$$P_i = \frac{\left(\frac{\lambda_1}{\mu_1}\right)^i}{\sum_{l=0}^{n_1} \left(\frac{\lambda_1}{\mu_1}\right)^l}, \qquad (10)$$

where $i=1,2,\ldots,n_1$.

We entered $\rho_i = \lambda_1/\mu_1$ – the reduced intensity of the first incoming stream. With:

$$P_i = \frac{\rho_1^i}{\sum_{l=0}^{n_1} \rho_1^l}, \qquad (11)$$

where $i=1,2,\ldots,n_1$.

Since the system has a solution under the condition that $\rho_1<1$, the sequence $1, \rho_i, \rho_1^2, \ldots, \rho_1^{n_1}$, forms a descending geometric progression with the first term equal to 1 and the denominator ρ. That is why:

$$\sum_{l=0}^{n_1} \rho_1^l = \frac{1-\rho_1^{n_1+1}}{\rho_1}. \qquad (12)$$

Then the probability distribution of the group states is as follows:

$$P_i = \frac{\rho_1^i (1-\rho_1)}{1-\rho_1^{n_1+1}}, \qquad (13)$$

where $i=1,2,\ldots,n_1$.

Conditional probability distributions of system states $\widehat{P}_{ik}$ were found (conditional probability of the system being in the k-th state of the i-th layer, provided it is in this layer) inside each layer. These distributions are obviously the same because the graph of states and transitions for each of them takes the same form, shown in Fig. 4.

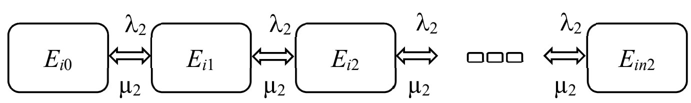

Fig. 4. Graph of states and transitions inside the i-th layer

The conditional probabilities of the states of the system are found similar to (3) to (8):

$$\widehat{P}_{i,k} = \frac{\rho_2^k (1-\rho_2)}{1-\rho_2^{n_2+1}}, \qquad (14)$$

where $k=0,1,2,\ldots,n_2$, and $\rho_2 = \lambda_2/\mu_2$ is the reduced intensity of the second incoming stream.

Then the unconditional probability of the system being in the k-th state of the i-th layer, that is, the state E_{ik} of the real system, is determined by the ratio:

$$P_{i,k} = \widehat{P}_{ik} \cdot P_i = \frac{\rho_1^i \cdot \rho_2^k (1-\rho_1)(1-\rho_2)}{\left(1-\rho_1^{n_1+1}\right)\left(1-\rho_2^{n_2+1}\right)}, \qquad (15)$$

where $i=0,1,\ldots,n_1$, $k=0,1,\ldots,n_2$.

Next, knowing the probabilities of all states of the system model, it is possible to calculate QoS indicators, such as network node and communication channel failure rates, packet losses, packet delay, and others. For example, to calculate the probability of packet loss, it is necessary to sum up the probabilities of critical states, which are shown in Fig. 5.

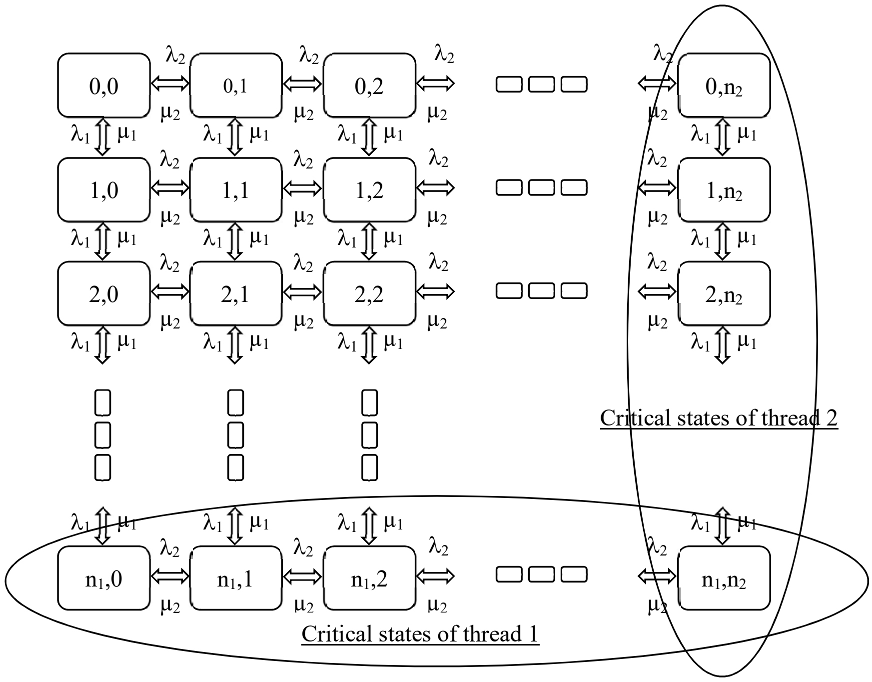

Fig. 5. Critical states of a system model with two threads that have their own amount of memory for queues

The critical states of the system are considered, for example the E_{n10} state; it corresponds to a real situation when the queue of packets of the first stream is full, and there are no packets of the second stream in the system. If another packet of the first stream arrives at the input, the model predicts that it will be filtered, since there is no room for it in the queue. But due to the fact that the queue for packets of the second flow is empty, half of the node's memory is free for receiving packets. Thus, the proposed model needs to be corrected by taking into account the shared memory volume.

The probability of system failure is calculated:

$$P_{\text{failure\_udp}}=\sum_{i=0}^{n_1}P_{i,n_2}+\sum_{k=0}^{n_2-1}P_{n_1,k}=$$
$$=\sum_{i=0}^{n_1}\frac{\rho_1^i\cdot\rho_2^{n_2}\left(1-\rho_1\right)\left(1-\rho_2\right)}{\left(1-\rho_1^{n_1+1}\right)\left(1-\rho_2^{n_2+1}\right)}+$$
$$+\sum_{k=0}^{n_2-1}\frac{\rho_1^{n_1}\cdot\rho_2^{k}\left(1-\rho_1\right)\left(1-\rho_2\right)}{\left(1-\rho_1^{n_1+1}\right)\left(1-\rho_2^{n_2+1}\right)}. \qquad (16)$$

The probability of system failure, described as the probability of packet loss, corresponds to this situation in the model by the extreme states of the system, the probabilities of which must be summed up.

5. 2. Markov model of a network node that serves one stream of Transmission Control Protocol packets

The model of a node of an electronic communication network is considered, at the input of which packets are received from a source with an intensity λ_1. Arriving packets are served (transmitted to the next node) with an intensity μ_1, and their copies are placed in the router's memory until confirmation of successful delivery; thereby removing the package from memory. The intensity of removing one packet from memory in case of successful transmission is μ_2. If the sent packet does not reach the recipient, its backup copy is moved to the general queue for resending. Let the intensity of occurrence of transmission errors of one packet be equal to λ_2. The memory of the router can contain n packets, among which there can be both copies of already transmitted packets waiting for confirmation, and new ones queued up for service (transmission).

It is assumed that the intervals in the streams of events related to the arrival of packets at the node's input, their transmission, the occurrence of errors, and the deletion of successfully transmitted packets are exponentially distributed. Then the apparatus of Markov processes can be used to analyze the system.

A graph of states and transitions of the described system was constructed (Fig. 6).

Here, state (i, j) corresponds to the situation when the system stores i copies of various transmitted packets awaiting confirmation of successful delivery to the addressee, and j new packets from the source awaiting service (transmission).

Thus, the purpose of the work is to find the probabilities of the described system being in multiple states, finding the probability of system failure and the probability of initiating a restraining packet. The set of system states is divided into subsets as follows (Fig. 7). Elements whose sum of indices is equal to i will fall into the subset E_i. For example, E_i={(0,0)}, E_1={(1,0),(0,1)}, E_2={(2,0),(1,1),(0,2)}.

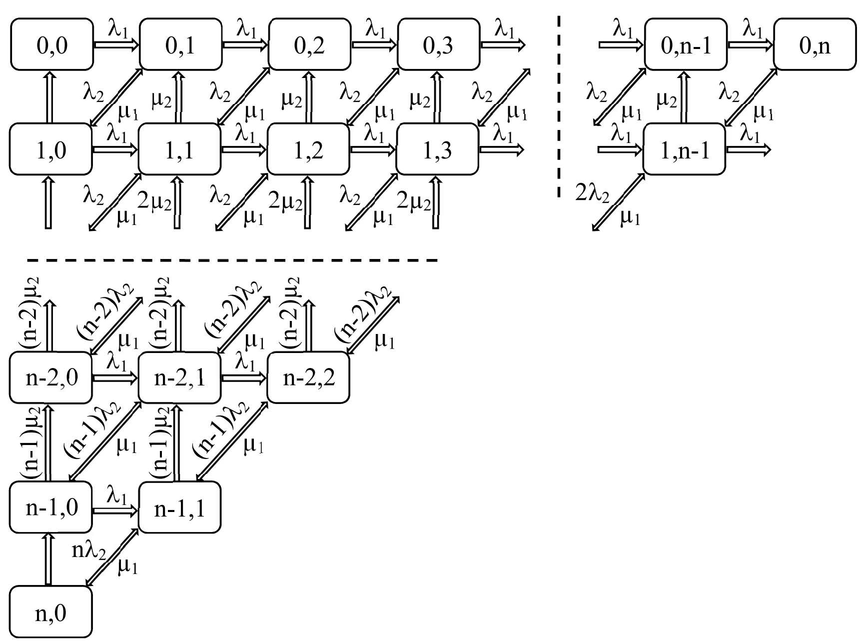

Fig. 6. Graph of states and transitions of the packet transmission system

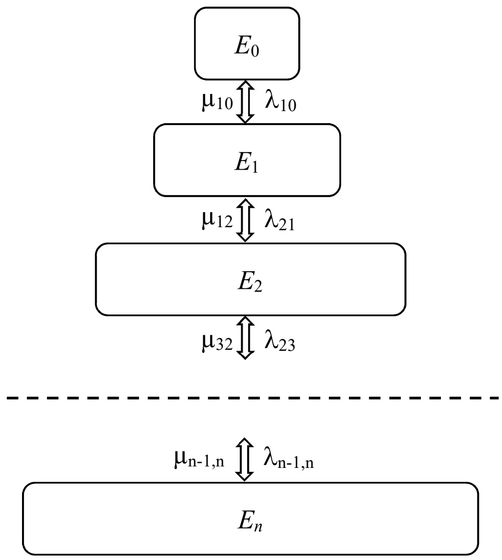

Fig. 7. Graph of group states and transitions

The balance equation for the resulting graph is compiled:

$$\begin{cases}\mu_{10}P_1-\lambda_{01}P_0=0,\\ \mu_{21}P_2+\lambda_{01}P_0-(\lambda_{12}+\mu_{10})P_1=0,\\ \dots\dots\dots\dots\dots\dots\\ \lambda_{n-1,n}P_{n-1}-\mu_{n,n-1}P_n=0.\end{cases} \tag{17}$$

Here, P_k is the probability of the system being in the group state k, $\mu_{k,k-1}$ the intensity of transitions from the group state k to the group state $k-1$, $\lambda_{k,k+1}$ the intensity of transitions from the group state k to the group state $k+1$, $k=0,1,2,\dots,n$.

Let's introduce $\widehat{P}_{i,k-i}$ – the conditional probability of being in the i-th state of the k-th layer, under the condition of being in this layer.

Then the probability of transitions between layers is equal to:

$$\lambda_{k,k+1}=\sum_{i=0}^{k}\lambda_1\widehat{P}_{i,k-i}=\lambda_1\sum_{i=0}^{k}\widehat{P}_{i,k-i}=\lambda_1, \tag{18}$$

$$\mu_{k,k-1}=\sum_{i=0}^{k}k\mu_2\widehat{P}_{i,k-i}=k\mu_2\sum_{i=0}^{k}\widehat{P}_{i,k-i}=k\mu_2. \tag{19}$$

The balance equation with condition (18), (19) has been rewritten:

$$\begin{cases}\mu_2P_1-\lambda_1P_0=0,\\ 2\mu_2P_2+\lambda_1P_0-(\lambda_1+\mu_2)P_1=0,\\ 3\mu_3P_3+\lambda_1P_1-(\lambda_1+2\mu_2)P_2=0,\\ \dots\dots\dots\dots\dots\\ \lambda_1P_{n-1}-n\mu_2P_n=0.\end{cases} \tag{20}$$

We introduced $z_k=k\mu_2P_k-\lambda_1P_{k-1}$ and, by substituting z_k in (20), we obtained:

$$\begin{cases}z_1=0,\\ z_2-z_1=0,\\ z_3-z_2=0,\ P_1=\dfrac{\lambda_1}{\mu_2}P_0,\\ \dots\dots\dots\\ z_n=0.\end{cases} \tag{21}$$

Hence, it was found:

$$z_k=k\mu_2P_k-\lambda_1P_{k-1}=0. \tag{22}$$

Using (22), the probability of system states due to P_0 is given:

$$P_2=\frac{\lambda_1}{2\mu_2}P_1=\frac{\lambda_1}{2\mu_2}\frac{\lambda_1}{\mu_2}P_0=\frac{\lambda_1^2}{2\mu_2^2}P_0,$$

$$P_3=\frac{\lambda_1}{3\mu_2}P_2=\frac{\lambda_1}{3\mu_2}\frac{\lambda_1}{2\mu_2}\frac{\lambda_1}{\mu_2}P_0=\frac{\lambda_1^3}{3!\mu_2^3}P_0,$$

....

$$P_k=\frac{\lambda_1}{k\mu_2}P_{k-1}=\frac{\lambda_1^k}{k!\mu_2^k}P_0,$$

where $k=1,2,\dots,n$.

We introduced $\rho_2=\lambda_1/\mu_2$. From the normalization condition $\sum_{i=0}^{n}P_i=1$, we get:

$$P_0+\rho P_0+\frac{\rho^2}{2!}P_0+\frac{\rho^3}{3!}P_0+\ldots+\frac{\rho^n}{n!}P_0=1,$$

$$P_0\left(1+\rho+\frac{\rho^2}{2!}+\frac{\rho^3}{3!}+\ldots+\frac{\rho^n}{n!}\right)=1.$$

Since it is clear from physical considerations that $\lambda_1<\mu_2$, then for sufficiently large n we have:

$$1+\rho+\frac{\rho^2}{2!}+\frac{\rho^3}{3!}+\ldots+\frac{\rho^n}{n!}\approx e^{\rho}.$$

Then:

$$P_0\approx e^{-\rho}.$$

In this case:

$$P_k=\frac{e^{-\rho}\rho^k}{k!}, \tag{23}$$

where $k=0,1,\dots,n$.

Thus, the probabilities of group states of the system were found. We have now found the distribution of state probabilities within each layer. We considered the graph of states and transitions for the k layer (Fig. 8).

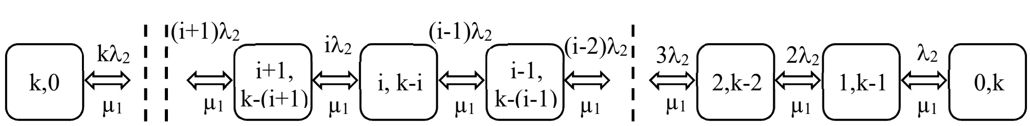

Fig. 8. Graph of states and transitions for the k-th layer

The balance equation is constructed:

$$\begin{cases}\lambda_2\widehat{P}_{1,k-1}-\mu_1\widehat{P}_{0,k}=0,\\ 2\lambda_2\widehat{P}_{2,k-2}+\mu_1\widehat{P}_{0,k}-\lambda_2\widehat{P}_{1,k-1}-\mu_1\widehat{P}_{1,k-1}=0,\\ \dots\dots\dots\dots\dots\dots\\ (i+1)\lambda_2\widehat{P}_{i+1,k-(i+1)}+\mu_1\widehat{P}_{i-1,k-(i-1)}-i\lambda_2\widehat{P}_{i,k-i}-\mu_1\widehat{P}_{i,k-i}=0,\\ \dots\dots\dots\dots\dots\dots\\ k\lambda_2\widehat{P}_{k,0}-\mu_1\widehat{P}_{k-1,1}=0.\end{cases} \quad (24)$$

Substitution of variables $Z_i=i\lambda_2\widehat{P}_{i,k-i}-\mu_1\widehat{P}_{i-1,k-(i-1)}$, was performed, which leads system (24) to the form:

$$\begin{cases}Z_1=0,\\ Z_2-Z_1=0,\\ Z_3-Z_2=0,\\ -----\\ Z_k=0.\end{cases} \quad (25)$$

Hence, it follows that $Z_i=0$, $i=1, \dots, k$, therefore, $i\lambda_2\widehat{P}_{i,k-i}-\mu_1\widehat{P}_{i-1,k-(i-1)}=0$.

Then:

$$\widehat{P}_{1,k-1}=\frac{\mu_1}{\lambda_2}\widehat{P}_{0,k},$$

$$\widehat{P}_{2,k-2}=\frac{\mu_1}{2\lambda_2}\widehat{P}_{1,k-1}=\frac{\mu_1}{2\lambda_2}\frac{\mu_1}{\lambda_2}\widehat{P}_{0,k}=\frac{\mu_1^2}{2!\lambda_2^2}\widehat{P}_{0,k},$$

....

$$\widehat{P}_{i,k-i}=\frac{\mu_1}{i\lambda_2}\widehat{P}_{i-1,k-(i-1)}=\frac{\mu_1^i}{i!\lambda_2^i}\widehat{P}_{0,k},$$

where $i=1, 2, \dots, k$.

We introduced $\alpha=\mu_1/\lambda_2$. From the normalization condition $\sum_{i=0}^{k}\widehat{P}_{i,k-i}=1$, the following is obtained:

$$\widehat{P}_{0,k}+\frac{\alpha}{1!}\widehat{P}_{0,k}+\frac{\alpha^2}{2!}\widehat{P}_{0,k}+\frac{\alpha^3}{3!}\widehat{P}_{0,k}+\dots+\frac{\alpha^k}{k!}\widehat{P}_{0,k}=1,$$

$$\widehat{P}_{0,k}\left(1+\frac{\alpha}{1!}+\frac{\alpha^2}{2!}+\frac{\alpha^3}{3!}+\dots+\frac{\alpha^k}{k!}\right)=1.$$

Similar to the previous one, we have:

$$\widehat{P}_{0,k}\approx e^{-\alpha}.$$

In this case:

$$\widehat{P}_{i,k-i}=\frac{e^{-\alpha}\alpha^i}{i!}, \quad (26)$$

where $i=1, 2, \dots, k$.

Thus, the conditional probability of the system being in the state $(i, k-i)$ under the condition of being in the k layer is found. Then the unconditional probability of finding the system may (i, j) equal to:

$$P_{i,j}=P_{(i+j)}\times\widehat{P}_{i,j}=\frac{\rho^{i+j}\alpha^i}{(i+j)!i!}e^{-(\rho+\alpha)}. \quad (27)$$

Thus, a relation was obtained to calculate the probabilities of the system being on many states.

Then the probability of failure:

$$P_{\text{failure\_tcp}}=\sum_{i+j=n}P_{i,j}=\frac{\rho^n}{n!}e^{-(\rho+\alpha)}\sum_{i=0}^{n}\frac{\alpha^i}{i!}=\frac{\rho^n}{n!}e^{-\rho}, \quad (28)$$

is equal to the probability of being in the n layer, and the probability of the router emitting a restraining packet [3] is equal to the probability of the system being in a group state, the number of which is calculated as the smallest integer greater than [0.8*n].

5. 3. Comparison of the models built and calculation results

Markov models of UDP and TCP traffic were constructed. To describe traffic with guaranteed delivery in the network model, additional states and transitions must be added, which make the calculations of the failure probabilities $P_{\text{failure\_udp}}$ and $P_{\text{failure\_tcp}}$ in the models different from each other according to ratios (16) and (28), respectively. To compare these values, graphs of the dependence of the probability of system failure on the intensity of incoming traffic were constructed, Fig. 9, for the number of threads from two to five.

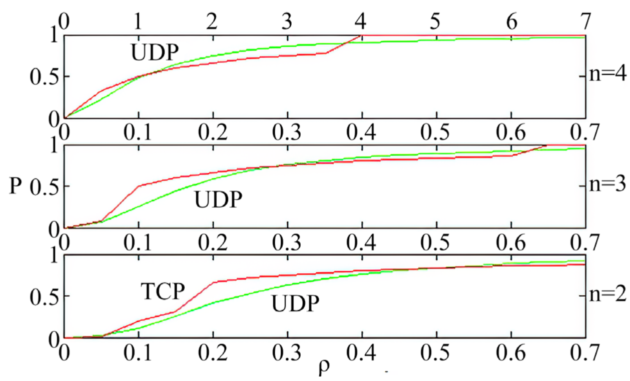

Fig. 9. Comparison of $P_{\text{failure\_udp}}$ and $P_{\text{failure\_tcp}}$ and different traffic intensity and different number of threads

More failures and packet queue lengths at a network node during peak load typically occur with TCP traffic compared to UDP traffic. The main reason is that TCP uses flow control and rate-limiting mechanisms to avoid network congestion and ensure efficient data transfer between nodes. These mechanisms can cause TCP to create more packet queues to ensure reliability and correct delivery order.

In contrast, UDP has no such built-in mechanisms, so it can result in less packet queuing. However, this can also mean that under heavy load, UDP may drop packets without attempting to resend them or adjust the transmission rate.

6. Discussion of results of the models built and their calculations

In the work, the models of the network node under the modes of UDP and TCP traffic service were built; the differences in the models are caused by taking into account the differences in the behavior of network protocols.

Fig. 1 shows the Markov model of a network node with UDP traffic; the problem can be solved by grouping the layers of the model, as shown in Fig. 2. The behavior model of a separate layer of the original model is shown in Fig. 3, 4, and the critical states of the original model are shown in Fig. 5.

Unlike UDP traffic, for TCP traffic it is necessary to simulate packet retransmission in case of packet loss. Fig. 6 shows that an additional dimensionally is added to take into account retransmission of TCP packets, and in Fig. 7, 8 it is decomposed into layers. In turn, Fig. 9 shows that the QoS indicators in the case of TCP traffic behave differently from the case of UDP, when, for example, the dependence of queue length on traffic intensity coincides with the classic plots for MSS [11].

In contrast to work [9], our study takes into account the essence of network protocols with and without guaranteed packet delivery. Also, in [7], a network node is considered as a collection of queues, each of which has its own memory volume, which is not natural, and in the current paper a model with shared memory is proposed due to the triangular shape of the graph of states and transitions. However, for the correct operation of the model, it is important that the lengths of packets of different flows are almost equal, as in [4].

In practice, the proposed models of operation of the network node have restrictions on their use. They can be used only under the condition of modeling traffic on the network layer of the ISO/OSI model. Their work was not checked on other layers. The proposed Markov models, on par with other Markov models, have a classical restriction on the law of random variables. It describes a stochastic process. That is, their calculation can be performed only under the assumption that the incoming packet flow is a simpler Poisson flow [2].

The model data cannot be used in this form if the flow is, for example, self-similar. This limitation can be eliminated in the future due to the Markov approximation of the incoming traffic. This can be done using the Markov approximation procedure.

The advancement of our research is connected, first of all, with the development of network protocols, which are constantly changing. It would be very interesting to consider the sliding window algorithm of the TCP protocol, which is not taken into account in this work. Also, further research should focus on software defined networks (SDN) network models.

This study contributes to the development of the theory and practice of network technologies. The resulting models could be used to analyze and predict the behavior of UDP and TCP traffic in actual networks.

This work might be useful for network hardware and software developers, as well as network design and optimization professionals.

7. Conclusions

1. A model of a network node serving UDP traffic was built using the mathematical apparatus of Markov mass service systems. Unlike existing models, the proposed model takes into account the heterogeneity of the traffic due to the increase in the dimensionality of the system. For this case, the probabilities of the system states were calculated, and the ratio for QoS indicators in the case of UDP traffic was additionally obtained.

2. Using the mathematical apparatus of Markov mass service systems, a model of a network node serving TCP traffic was built. Unlike existing models, retransmission of lost packets is taken into account here, this was achieved due to the additional dimension of the system. The model takes into account the common memory for all threads, which corresponds to the real situation, increases the adequacy of the model in comparison with existing models for which the memory for each thread is fixed. Probabilities of system states are calculated for this model. We have additionally obtained ratios for QoS indicators (quality of service) in the case of TCP traffic. The model built and our findings allow us to better understand the behavior of TCP traffic in the network and to optimize the QoS parameters for this type of traffic.

3. The derived ratios for QoS indicators make it possible to evaluate the quality of service of UDP and TCP traffic in network nodes, take into account their differences, and optimize network resources. It is shown that taking into account TCP traffic, in contrast to standard models that only take into account UDP traffic, worsens the queue length indicators by 3 % at peak load, and the graph has a stepped shape, which distinguishes it from the curve that is built analytically using classic MSS formulas.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data cannot be provided for the reasons stated in the data availability statement.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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