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Comparative Analysis of Options for Organizing Internet Traffic Exchange in Territorially Distributed Communication Networks

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ABSTRACT

The choice of the structure of the internet traffic exchange network is an urgent task for countries located with large areas. A mathematical model of this network with two Internet exchange points (IXes) in the form of a queuing network has been developed and analyzed. The proposed model, which, if necessary, can be generalized to the case of an arbitrary number of IXes, allows calculating the main characteristics of the network, determining its optimal parameters and analyzing alternative construction options: average round-trip delay (RTD), channel capacity, calculate the performance of traffic exchange nodes under reliability and cost constraints, and topology selection for the traffic exchange network, considering the main parameters. The results of calculations for Internet traffic exchange networks with uniform and significantly uneven loading of network channels are presented. An Internet traffic exchange network with several IXes can provide a lower delay, higher availability, and lower costs for implementation and commercial operation. In this case, a network with several IXes will enable the owners of these nodes and regional telecom operators to improve service and gain economic benefits.

Keywords: Internet exchange points; Internet traffic; Channel capacity; Telecom operators; Round-trip delay; Peering; Queuing network; Queuing theory.

INTRODUCTION

The development of telecommunications is currently oriented towards creating heterogeneous networks capable of providing a wide range of information services (telephony, mobile communications, data transmission, Internet, etc.) to network users with the required quality of service characteristics and corresponding to the concept of integrated communication networks space-air-ground-sea integrated network (SAGSIN) (Guo *et al.* 2021; Xu *et al.* 2023; Zhao *et al.* 2024). The enlarged structure of such a network, containing a ground segment (Ground+Sea), satellite communication networks (SCN), and various aerial systems, is shown in Fig. 1, where GEO is Geostationary Earth Orbit Satellites, MEO is Medium Earth Orbit Satellites, and LEO is Low Earth Orbit Satellites. A feature of SAGSIN is the widespread use, along with communications relay satellites, of unmanned aircraft systems: drones and high-altitude platform stations (Ahmadinejad and Falahati 2021; Amarasingam *et al.* 2022; Chechin *et al.* 2022; Idrissi *et al.* 2022; Mohsan *et al.* 2022; Xing *et al.* 2021). Such integration of various networks makes it possible to optimally distribute resources to increase the efficiency and reliability of information exchange, including through the dynamic management of information flows (Chechin *et al.* 2023).

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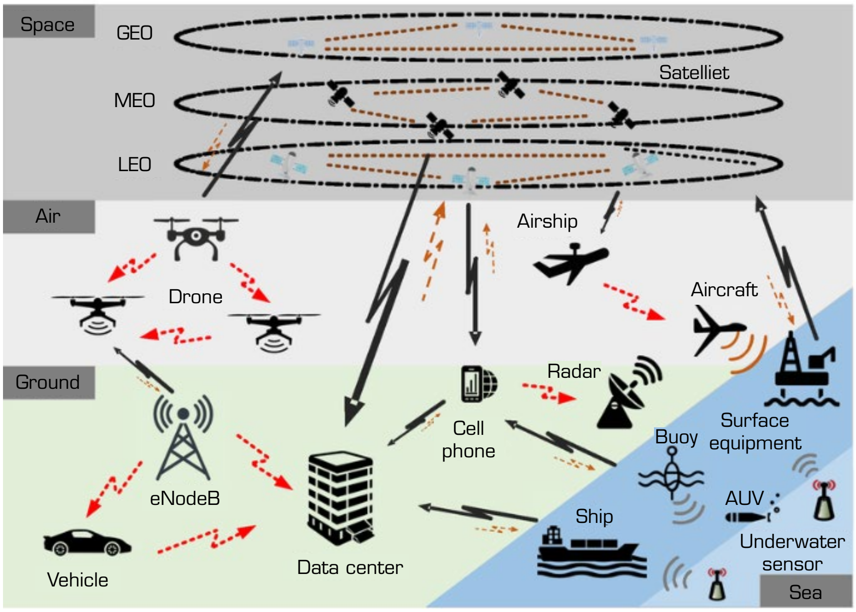


Source: Elaborated by the authors.
Figure 1. The framework of SAGSIN.

The emergence of SAGSIN communication networks is a logical continuation of the development of telecommunication networks and creates the prerequisites for the creation a unified communication network that combines the resources of all networks and integrates all types of services (audio, video, data). The relevance of creating such networks is explained by the constant growth in data traffic, as the demand for digital and online services grows. A report by Ericsson (2023) notes that global data traffic has grown by 60% over the past decade and this trend is set to continue. Annual data consumption in most regions is projected to grow by 20-30% over the next few years, with monthly global internet traffic expected to reach 563 exabytes by the end of 2029. Therefore, one of the important functions of SAGSIN is to organize the transmission of an ever-increasing volume of Internet traffic with maximum efficiency and minimal costs.

An effective solution for increasing the availability of the Internet for users, reducing the cost of communication services, stimulating the development of the Internet market, reducing the volume of transit traffic and optimizing routing is the use of Internet exchange points (IXes), which provide the exchange of Internet traffic between various telecom operators (Ager *et al.* 2012; Lambrechts and Sinha 2019; Xu *et al.* 2004). The scientific and technical literature discusses various aspects of the application of IXes in the context of the introduction of new information technologies. For example, SpaceX and OneWeb plan to use IXes in their Starlink satellite networks as connection points to other networks and exchange traffic, while network users will be able to connect directly to Starlink and OneWeb through IXes (Pessoa Filho 2021). This approach will not only improve network performance, but also significantly reduce the cost of servicing Internet traffic, as confirmed by research results (Alam *et al.* 2021; Hoeschele *et al.* 2021). It should also be noted that IXes can be used not only for the transmission of Internet traffic, but also for other applications where high efficiency and reliability are required, such as in air traffic management systems (Sampaio *et al.* 2022).

In the case of small national communication networks, which is typical for most countries of the world, the exchange of Internet traffic is organized in one or two nodes. For example, in Frankfurt it is DE-CIX, in Amsterdam it is AMS-IX, in Moscow it is MSK-IX, etc. (a complete list of IXes in the world linked to a map can be found, for example, on www.internetexchangemap.com). IXes establish peering interactions between telecom operators at lower costs and with greater efficiency compared to the organization of pairwise direct physical connections. IXes nodes provide such basic communication services such as shared peering, private peering, route server network service, Private VLAN access and point-to-point (p2p) channeling using Border Gateway Protocol. A description and study of the above and other peering options in networks with one IX are given, for example, in Ahmad and

Guha (2010), Hernández *et al.* (2018), Lambrechts and Sinha (2019), Lee and Son (2021), Lv *et al.* (2018), O'Briain *et al.* (2020), Ofa (2021), and Prados-Garzon *et al.* (2021). However, the authors are not aware of any work, except for Chechin (2019), that conducts a comparative analysis of options for building an Internet traffic exchange network with one or several switching nodes.

This article explores the issues of building an Internet traffic exchange network for the case of geographically distributed networks, where IXes and telecom operators are at a considerable distances from each other, which is typical for countries such as China, India, Russia, United States, and several others. Performance indicators used when comparing different network construction options (one or more IXes nodes) include the average round-trip delay (RTD), throughput of the communication network and exchange nodes, reliability of channels and the entire network, as well as its cost are used. This article extends and adds to the models outlined in Chechin (2019) and contains specific numerical results of a comparative analysis of options for building Internet traffic exchange networks.

Theoretical basis

The structure of the modern Internet is not tree-like and consists of a huge number of connections between various telecom operators without the use of a main router that processes all Internet traffic. Conceptually, the architecture of the Internet is a set of autonomous systems (AS) and a set of physical and logical connections between them that determine the path of traffic from one AS to another (Beiró *et al.* 2015; Pastor-Satorras and Vespignani 2004). AS are usually telecom operators, content delivery networks, and data centers (Frangoudis *et al.* 2017). The transfer of data between different AS is made possible by their support for common routing protocols and addressing schemes. The operator of each AS independently provides interaction with other similar systems either through a higher-level operator or through IXes, the main purpose of which is to organize data exchange between different AS directly, and not through external networks.

The conditions of interaction in IXes case are determined by the agreements of AS operators that are connected to these IXes. The use of a special IXes infrastructure allows AS operators to use productive equipment, ensure high reliability and security of data transfer, and also reduce the cost of organizing interaction between networks and traffic transit (Jensen 2012), increase the availability of information resources for users of other AS connected to these IXes, reduce delay and amount of transit traffic, and optimize routing between AS.

The first IXes began to appear in 1994 in major European cities: London (LINX), Frankfurt (DE-CIX), Amsterdam (AMS-IX), and Moscow (MSK-IX). Now, their number worldwide exceeds 500. In Russia, in addition to MSK-IX, there are about a dozen other less powerful IXes (Saint Petersburg, Rostov-on-Don, Samara, Yekaterinburg, etc.), but they serve a small number of AS and are regional. The main Internet traffic exchange center in Russia is MSK-IX, through which up to 90% of all traffic goes, serving more than 1,000 telecommunications companies.

MSK-IX performs the following main tasks (Ilyin 2020):

- Public and private peering for content delivery, improving the availability of online services, reducing traffic transit costs, and reserving network routes.
- Access via a local network route to the root DNS servers and DNS servers of national domains RU and RF.
- Organization of virtual channels and virtual private networks (802.1 VLAN).
- Increasing the speed of access to content for subscribers.
- Distributed content delivery in regions.
- Transmission and reception of digital television signals.

The efficiency of IXes nodes increases with the number of connected participants. To small countries, it is rational to use one IX node. For large countries, the use of one node IX with large distances of several thousand kilometers between it and regional RTD operators, that is, the time interval between the request transmitted by the network user and the response received (Reyouchi *et al.* 2013), turns out to be quite large and can reach several tens of milliseconds.

The second problem of extended communication channels is to provide a given reliability: a specified value of service level availability (SLA) (Durvy *et al.* 2003). To address this, redundancy of communication lines is often used, which, in turn, leads to an increase in the costs for regional operators.

Thus, on the one hand, an increase in the number of IXes nodes with the placement of cache servers in them leads to a decrease in RTD, an increase in SLA and a decrease in the costs for telecom operators for renting communication channels to IXes. On the other hand, it increases the costs for owners of IXes nodes for creating infrastructure. Obviously, there is an optimal number of IXes nodes that maximizes the given performance indicators of the Internet traffic exchange network. At the same time, such basic parameters as the specified level of SLA reliability and the volume of Internet traffic, the number of telecom operators, their territorial location, the cost of renting communication channels, the cost of creating IXes node infrastructure, etc., are the limitations. The problem of choosing the number of IXes is similar to the problem of choosing the optimal location of distribution warehouses, the solution to which uses linear programming methods, combinatorial methods, dynamic programming methods, set theory, and vector optimization. However, the mathematical models developed using these methods are quite abstract, and the solutions are obtained in an implicit form.

This article proposes a mathematical model for evaluating the performance indicators of Internet traffic exchange networks for an arbitrary number of IXes. Using the example of comparing the characteristics of Internet traffic exchange networks with one and two IXes, it is shown that, under certain conditions, the second option provides the best performance indicators.

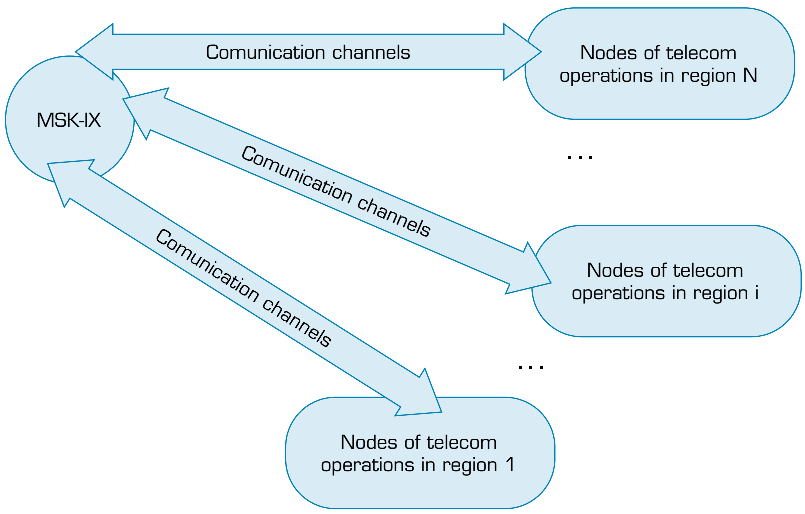
METHODOLOGY

As a mathematical apparatus for building models of the Internet traffic exchange network, we will use queuing theory, according to which the communication network is represented as a queuing network, and nodes and communication channels, in general case, are multichannel queuing systems with queues of unlimited volume (Kleinrock 1975). Also, to simplify the analysis, we will assume that information flows in the Internet traffic exchange network are Poisson, and the volumes of transmitted messages have an exponential distribution.

Since the purpose of the article is not to study the fine structure of Internet traffic exchange methods (peering and IP transit), the information exchange between operators and between operators and IXes is represented by traffic intensities and their volumes. In other words, regardless of the peering and IP transit structure, we will continue to operate with information interaction processes at the level of flow intensities and volumes of transmitted information.

Network model for exchanging Internet traffic through a single node

As it was noted earlier, in Russia, the main volume of Internet traffic passes through MSK-IX, which is reflected in the enlarged diagram (Fig. 2).



Source: Elaborated by the authors.

Figure 2. Scheme of organizing an Internet traffic exchange network through one MSK-IX node.

To analyze the network, we introduce the following notation: λ_p is the intensity of traffic to MSK-IX from I regional operators with an average volume of requests V_z (bytes); λ_M is traffic intensity to MSK-IX from Moscow region operators; and q is the probability that the requested content with an average volume V_κ (bytes) is located on the servers of I regional operators.

The average message propagation delay from regional operators to MSK-IX is defined as $\tau_{av} = \frac{1}{\lambda_p}\sum_{i=1}^{I}\lambda_{pi}\tau_i$, where λ_{pi} and τ_i are, respectively, the intensity of request traffic from the i-th regional operator and the delay in the propagation of these messages from the i-th operator to MSK-IX, $\lambda_p = \sum_{i=1}^{I}\lambda_{pi}$, and $\tau_i = \frac{l_i}{0.7s}$ is propagation time of signals in the optical communication channel from the i-th operator to MSK-IX, where c is the speed of light.

Incoming traffic to MSK-IX node will be $\lambda_{MSK}^{in} = (\lambda_p + \lambda_M)(1-q)$.

S_{FC} and S_{RC} are the total throughput capacity of "forward" channels to MSK (FC) and "reverse" channels from MSK-IX (RC) in the lines between regional operators and MSK-IX, S_{MSK} is performance (bandwidth) MSK-IX, and M_C is the number of communication channels (usually 10 Gbit·s) between regional operators and MSK-IX, in the general case $M_C \geq I$. Therefore, the throughput of one channel S_{FC1}, in the general case, will be M_C times less. As a rule, the channels are duplex, so $S_{FC} = S_{RC}$. The values of μ_{FC} and μ_{RC} are the reciprocal of the average length (volume) of messages in the "forward" and "reverse" communication channels between MSK-IX and regional operators, and μ_{MSK} is the reciprocal of the average volume of information circulating in MSK-IX.

We determine the average delay of messages in FC. The traffic intensity in FC is $\lambda_{FC} = \lambda_p(1+q) + \lambda_M q$, and the average volume of messages transmitted in FC: $V_{FC} = \frac{\lambda_p}{\lambda_{FC}}V_z + \frac{(\lambda_M+\lambda_p)q}{\lambda_{FC}}V_\kappa$, then respectively $\mu^{-1} = V_{FC}$.

The average message transmission delay in FC can be calculated by the well-known formula for a queuing system of the type $M/M/m$:

$$T_{FC} = \frac{m}{\mu_{FC}S_{FC}} + \frac{P_m}{\mu_{FC}S_{FC}(1-\rho_{FC})} + \tau_{av}, \tag{1}$$

where $\rho_{FC} = \frac{\lambda_{FC}}{\mu_{FC}S_{FC}}$ is loading of m direct channels and P_m is the probability that all m channels are busy:

$$P_m = \frac{P_0(m\rho_{FC})^m}{(1-\rho_{FC})m!}, \tag{2}$$

P_0 is the probability that the channels are free (idle):

$$P_0 = \left[\frac{(m\rho_{FC})^m}{(1-\rho_{FC})m!} + \sum_{k=0}^{m-1}\frac{(m\rho_{FC})^k}{k!}\right]^{-1}. \tag{3}$$

We determine the average delay of messages in MSK-IX. The average volume of one message circulating in MSK-IX is $V_{MSK} = \frac{(\lambda_M+\lambda_p)}{\lambda_{MSK}^{in}}(V_z + V_\kappa)(1-q) + \frac{(\lambda_M+\lambda_p)q}{\lambda_{MSK}^{in}}V_\kappa$, respectively $\mu_{MSK}^{1} = V_{MSK}$, and the load is calculated as $\rho_{MSK} = \frac{\lambda_{MSK}}{\mu_{MSK}S_{MSK}} = \frac{(\lambda_M+\lambda_p)(1-q)}{\mu_{MSK}S_{MSK}}$.

For MSK-IX model in the form of N-channel queuing system with C_{MSK} bandwidth, the average delay is calculated similarly to Eqs. 1–3 with the appropriate replacements:

$$T_{MSK} = \frac{N}{\mu_{MSK}S_{MSK}} + \frac{P_N}{\mu_{MSK}S_{MSK}(1-\rho_{MSK})} \tag{4}$$

$$P_N = \frac{P_0(N\rho_{MSK})^N}{(1-\rho_{MSK})N!},\ P_0 = \left[\frac{(N\rho_{MSK})^N}{(1-\rho_{MSK})N!} + \sum_{k=0}^{N-1}\frac{(N\rho_{MSK})^k}{k!}\right]^{-1}. \tag{5}$$

The intensity of traffic in the "reverse" channels and the main parameters of the model are equal:

$$\lambda_{RC} = \lambda_p + (\lambda_M + \lambda_p)q; V_{RC} = \frac{\lambda_p}{\lambda_{RC}}V_\kappa + \frac{(\lambda_M+\lambda_p)q}{\lambda_{RC}}V_z;\ \mu_{RC}^{-1} = V_{RC};\ \rho_{RC} = \frac{\lambda_{RC}}{\mu_{RC}S_{RC}}. \tag{6}$$

$$\lambda_{RC} = \lambda_p + (\lambda_M + \lambda_p)q; V_{RC} = \frac{\lambda_p}{\lambda_{RC}}V_\kappa + \frac{(\lambda_M+\lambda_p)q}{\lambda_{RC}}V_z;\ \mu_{RC}^{-1} = V_{RC};\ \rho_{RC} = \frac{\lambda_{RC}}{\mu_{RC}S_{RC}}. \tag{7}$$

The average delay in RC is calculated similarly to Eqs. 1–3 with appropriate changes of variables:

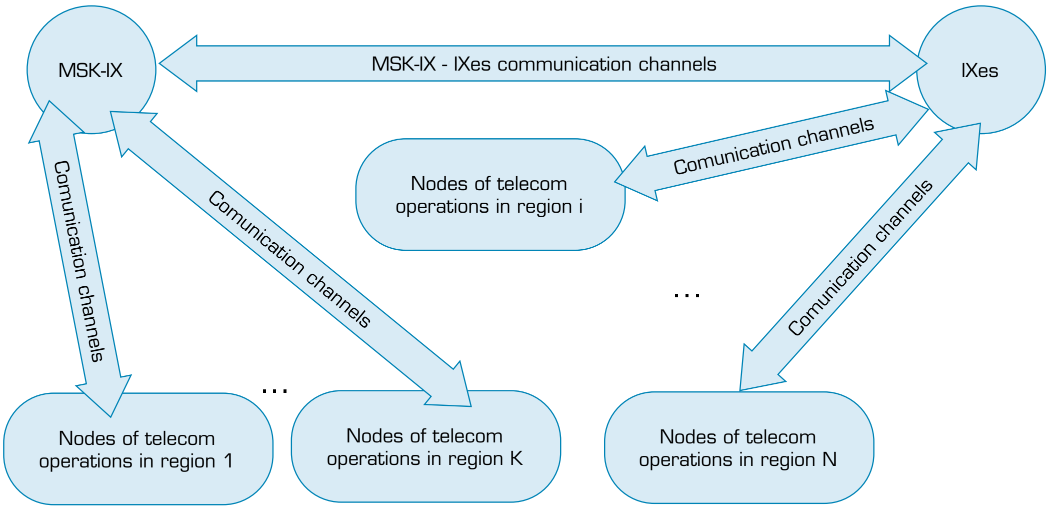
$$T_{RC} = \frac{m}{\mu_{RC} S_{RC}} + \frac{P_m}{\mu_{RC} S_{RC}(1-\rho_{RC})} + \tau_{av} \quad (8)$$

Finally, the average delay of messages in an exchange network with one IX is calculated as a weighted average (Chechin 2019):

$$\mathrm{T} = \frac{\lambda_{MSK}}{\lambda_{MSK}^{in}} T_{MSK} + \frac{\lambda_{\Pi K}}{\lambda_{MSK}^{in}} T_{FC} + \frac{\lambda_{RC}}{\lambda_{MSK}^{in}} T_{RC} \quad (9)$$

Internet traffic exchange network with multiple IXes

To simplify, we consider a network model with two IXes (Fig. 3), the results of which can be generalized to an arbitrary number of IXes.



Source: Elaborated by the authors.

Figure 3. Scheme of organizing an Internet traffic exchange network using two IXes.

We denote nodes with identical content as MSK-IX and IXes. There are M regional nodes, $M \in I$, attached to MSK-IX. We denote by $K = (I - M)$ the number of regional nodes that exchange Internet traffic through node IXes.

We introduce the following notation: q_{MSK}, q_M, q_{IXes}, and q_K are the probabilities that the requested content is located in MSK-IX, on M nodes, in node IXes, or on the servers of one of the K regional nodes, respectively, and: $q_{MSK} + q_M + q_{IXes} + q_K = 1$; λ_{pm} and λ_{pk} are intensity of traffic to the exchange nodes MSK-IX, and IXes from the m-th ($m \in M$) and k-th ($k \in K$) regional operators, respectively. The traffic entering the network from M and K operators is defined as $\lambda_{pM} = \sum_{m=1}^{M} \lambda_{pm}$ and $\lambda_{pK} = \sum_{\kappa=1}^{K} \lambda_{p\kappa}$. Average message propagation time in communication channels from M operators to MSK-IX (τ'_p), from K operators to IXes (τ''_p) and between IXes and MSK-IX (τ'''_p):

$$\tau'_p = \frac{1}{\lambda_{pM}} \sum_{m-1}^{M} \lambda_{pm} \tau_m \; ; \; \tau''_p = \frac{1}{\lambda_{pK}} \sum_{\kappa-1}^{K} \lambda_{p\kappa} \tau_\kappa \; ; \; \tau'''_p = \frac{L_{IXes-MSK}}{0.7s}, \quad (10)$$

where $L_{IXes-MSK}$ is distance between IXes and MSK-IX.

The capacity of the communication channels between M regional nodes and MSK-IX, between K regional nodes and IXes, between MSK-IX and IXes, we denote, respectively, S_{FC}^{M} and S_{FC}^{M}, S_{FC}^{IXes} and S_{RC}^{IXes}, and $S_{FC}^{IXes\text{-}MSK}$ and $S_{RC}^{IXes\text{-}MSK}$.

The total incoming traffic in this case will be equal to $\lambda_{2IXes}^{in} = \lambda_M + \lambda_{pM} + \lambda_{pK}$.

There are seven segments in the analyzed information exchange model:

- Exchange node MSK-IX;
- “forward” communication channels between nodes MSK-IX and IXes: $N_{MSK-IXes\text{ - }IXes}$, through which cache server streams circulate;
- “forward” communication channels between M operators and exchange node MSK-IX;
- “forward” channels between K operators and exchange node IXes;
- “reverse” communication channels from MSK-IX and M operators;
- “Reverse” communication channels between MSK-IX and IXes nodes, through which streams of $N_{MSK-IXes\text{ - }IXes}$ cache servers circulate;
- "reverse” channels between K operators and exchange node IXes.

The expressions for the intensity of information flows in each of the sections have a similar structure, as for the exchange network through one IX (Chechin 2019):

- Incoming traffic in MSK and the average amount of information circulating in it:

$$\lambda_{MSK} = \lambda_M + \lambda_{pK} q_{MSK} + \lambda_{pM} + (\lambda_M + \lambda_{pK} + \lambda_{pM}) q_M + (\lambda_M + \lambda_{pM})(q_{IXes} + q_K) \quad (11)$$

$$\overline{V}_{MSK} = \frac{\lambda_M (V_з + \overline{V_K}) q_{MSK}}{\lambda_{MSK}} + \frac{\lambda_{pK}(V_з + \overline{V_K})}{\lambda_{MSK}} + \frac{\lambda_{pK} V_з (1 - q_{MSK})}{\lambda_{MSK}} + \frac{\lambda_{pM}(V_з + \overline{V_K}) q_{MSK}}{\lambda_{MSK}} + \frac{\lambda_{pM} V_з (1 - q_{MSK})}{\lambda_{MSK}} + \frac{(\lambda_M + \lambda_{pK}\, q_{MSK} + \lambda_{pM}) q_M}{\lambda_{MSK}} \overline{V_K} + \frac{(\lambda_M + \lambda_{pM})(q_{IX} + q_K)}{\lambda_{MSK}} \overline{V_K}. \quad (12)$$

As in previous cases, $1/\mu_{MSK} = \overline{V}_{MSK}$.

- Traffic in direct channels (IXes-MSK) and the average amount of information transmitted in them will be:

$$\lambda_{IXes-MSK} = \lambda_{pK}(q_{MSK} + q_M) + (\lambda_M + \lambda_{pM})(q_{IX} + q_K), \quad (13)$$

where the first term defines request traffic from K regional nodes to MSK with request volume, and the second is content traffic from nodes IXes and K to MSK with an average volume of each message $\overline{V_K}$;

- Average volume of messages:

$$\overline{V}_{IXes-MSK} = \frac{\lambda_{pK}(q_{MSK}+q_M)}{\lambda_{IXes-MSK}} V_z + \frac{(\lambda_M+\lambda_{pM})(q_{IX}+q_K)}{\lambda_{IXes-MSK}} \overline{V_K}, \quad (14)$$

$$a\ 1/\mu_{IXes-MSK} = \overline{V}_{IXes-MSK}. \quad (15)$$

- Intensity of traffic in direct channels (M-MSK) and the average amount of information transmitted in them:

$$\lambda_{M-\mathrm{MSK}} = \lambda_{pM} + \lambda_{pM} q_M + \lambda_M q_M + \lambda_{pK} q_M \quad (16)$$

where the first term represents the request traffic from M operators to MSK with the volume of each V_z, and the subsequent ones - content traffic from M regional nodes on requests from Moscow operators, IXes and K operators with an average volume $\overline{V_K}$

$$\overline{V}_{M-MSK} = \frac{\lambda_M}{\lambda_{M-MSK}} V_z + \frac{(\lambda_{pM}+\lambda_M+\lambda_{pK}) q_M}{\lambda_{M-MSK}} \overline{V_K}, \quad (17)$$

$$1/\mu_{M-MSK} = \overline{V}_{M-MSK}; \quad (18)$$

- Traffic intensity in direct channels (K-IXes) and the average amount of information transmitted in them:

$$\lambda_{K-IXes} = \lambda_{pK} + (\lambda_M + \lambda_{pM} + \lambda_{pK}) q_K, \quad (19)$$

$$\overline{V}_{K-IX} = \frac{\lambda_{pK}}{\lambda_{K-IX}} V_z + \frac{(\lambda_M+\lambda_{pM}+\lambda_{pK})q_K}{\lambda_{K-IXes}} \overline{V_K} \tag{20}$$

$$1/\mu_{K-IXes} = \overline{V}_{K-IXes}; \tag{21}$$

- Traffic intensity in reverse channels (MSK-*M*) and the average amount of information transmitted in them:

$$\lambda_{MSK-M} = (\lambda_M + \lambda_{pM} + \lambda_{pK})q_M + \lambda_{pM}, \tag{22}$$

$$\overline{V}_{MSK-M} = \frac{(\lambda_{pM}+\lambda_M+\lambda_{pK})q_M}{\lambda_{MSK-M}} V_z + \frac{\lambda_{pM}}{\lambda_{MSK-M}} \overline{V_K}, \tag{23}$$

$$1/\mu_{MSK-M} = \overline{V}_{MSK-M}; \tag{24}$$

- Traffic intensity in reverse channels (MSK-IX) and the average amount of information transmitted in them:

$$\lambda_{MSK-IX} = (\lambda_M + \lambda_{pM})(q_{IX} + q_K) + \lambda_{pK}(q_{IX} + q_M), \tag{25}$$

$$\overline{V}_{MSK-IX} = \frac{(\lambda_M+\lambda_{pM})(q_{IX}+q_K)}{\lambda_{MSK-IX}} V_z + \frac{\lambda_{pK}}{\lambda_{MSK-IX}} \overline{V_K}, \tag{26}$$

$$1/\mu_{MSK-IX} = \overline{V}_{MSK-IX}; \tag{27}$$

- Traffic intensity in reverse channels (IXes-*K*) and the average amount of information transmitted in them:

$$\lambda_{IXes-K} = (\lambda_M + \lambda_{pM} + \lambda_{pK})q_K + \lambda_{pK}, \tag{28}$$

$$\overline{V}_{IXes-K} = \frac{(\lambda_M+\lambda_{pM}+\lambda_{pK})q_K}{\lambda_{IXes-K}} V_z + \frac{\lambda_{pK}}{\lambda_{IXes-K}} \overline{V_K}, \tag{29}$$

$$1/\mu_{IXes-K} = \overline{V}_{IXes-K}. \tag{30}$$

The average delay of messages in the traffic exchange network in each section of the network is determined by Eqs. 1–30 with the corresponding substitutions of variables and values $\overline{\tau_p}'$, $\overline{\tau_p}''$ and $\overline{\tau_p}'''$. Therefore, the expression for the average delay in a network with two IXes is as follows:

$$\mathrm{T} = \frac{\lambda_{MSK}}{\lambda^{6x}_{2IXes}} T_{MSK} + \frac{\lambda_{IXes\text{-}MSK}}{\lambda^{6x}_{2IXes}} T_{FC(IXes\text{-}MSK)} + \frac{\lambda_{M-MSK}}{\lambda^{6x}_{2IXes}} T_{FC(M-MSK)} + \frac{\lambda_{K-IK}}{\lambda^{6x}_{2IXes}} T_{FC(K-IXes)} + \frac{\lambda_{MSK-M}}{\lambda^{6x}_{2IXes}} T_{RC(MSK-M)} + \frac{\lambda_{MSK\text{-}IX}}{\lambda^{6x}_{2IXes}} T_{RC(MSK\text{-}IX)} + \frac{\lambda_{IXes-K}}{\lambda^{6x}_{2IXes}} T_{RC(IXes-K)} \tag{31}$$

Model for analyzing the reliability of Internet traffic exchange network

Before moving on to the description of the model, we accept the following clarification. The reliability of communication channels is usually assessed by the availability factor or the probability that the channel is operational (these are different indicators, but in a stationary mode of operation their values coincide). The value of the service availability coefficient IXes is ensured at least 99.9%, and the typical value of the availability coefficient to K_G for communication channels varies between 95%-99.5% for channels without redundancy. Therefore, as the initial data for demonstrating the capabilities of the proposed model, the K_G value for IXes is taken as 1 (IXes are absolutely reliable), and the availability rate of communication channels with a length of 1,000 km from geographically distant operators to IXes is 95%. When exchanging Internet traffic through one IX, the reliability of d parallel communication channels from each of I regional nodes to MSK-IX node (or to IXes, in the case of a network with two traffic exchange nodes) is defined as

$$K_G = \prod_{i=1}^{d}(1 - K_{Gdi}), \quad (32)$$

where K_{Gdi} is availability factor of one of d_i communication channels from the i-th regional node (operator) to MSK-IX (or to IXes) with length L_i km.

The reliability of the entire Internet traffic exchange network can be determined by analogy, as it was when calculating the average network delay in Eqs. 9 –31, i.e., as a weighted average of the traffic intensity circulating in each communication channel

$$K_G = \frac{1}{\lambda_{\text{in}}}\prod_{i=1}^{I}\lambda_i K_{Gi}, \quad (33)$$

where λ^{in} is the network traffic and λ_i is the traffic intensity in the i-th channel.

It is customary to calculate the availability factors of terrestrial wire channels through the availability factors of composite short sections of a communication line with a length of 100 km or 13,900 km (standard for Russian communication lines) and a length of 2,500 km (G.602 international standard). Based on 100 km sections, the availability factor is calculated as follows (Komarnitsky 2005):

$$\text{K}_{G\,100} = \frac{(8760 - \mu_{fr}Tr)}{8760}, \quad (34)$$

where μ_{fr} [1/hour] is the failure rate of a 100 km communication link (number of failures per year), 8,760 is the number of hours per year, and T_r is the average communication link recovery time.

Then the availability factor of a communication line with a length of L_p then the availability factor of a communication line with a length of L_i kilometers is defined as $K_{GL} = \prod_{i=1}^{Q} K_{Gi}$, where Q is the number of hundred-kilometer sections on a communication line with a length of L km.

Cost indicators of the Internet traffic exchange network

When calculating the cost of the exchange network, we will take into account the cost of MSK-IX and IXes nodes: C_{MSK} and C_{IXes}, respectively, the cost of leasing communication channels to traffic exchange nodes by regional operators C_K, the cost of Internet traffic received from ports at exchange points: $C_{P\,MSK}$ and $C_{P\,IXes}$, respectively. An analysis of the existing tariffs of Russian telecom operators allows us to accept the cost of renting one communication channel with a bandwidth of 10 Gbit·s for a communication line with a length of L km proportional to the square root of the length of the operator's communication line to the Internet traffic exchange node (MSK-IX or IXes):

$$C_K = S_{1000}\sqrt{A} \quad (35)$$

where C_{1000} is the cost of renting a communication channel with a length of 1,000 km, A is the number of thousand-kilometer sections in a communication line with a length of L km. In some regions of the world, the dependence (Eq. 35) may be different, for example, proportional to the cube root in regions with a developed infrastructure of communication channels or be close to linear in regions with an undeveloped infrastructure of communication channels.

Then, as a first approximation, the cost of the exchange network C_Σ is determined as the sum of the costs of Internet traffic exchange nodes MSK-IX and/or (MSK-IX + IXes) and communication channels. In the general case, when calculating the cost of an exchange network, it is necessary to take into account, of course, other components: capital costs and operating costs.

RESULTS

As an example, when choosing the structure of an Internet traffic exchange network, we will use the following initial data corresponding to the parameters of the network existing in Russia:

- All operators are territorially dispersed across six regions of Russia (which corresponds to the federal districts).
- The total number of network channels $N = 24$ with a bandwidth of 10 Gbit·s each and a conditional cost of a communication channel with a length of 1,000 km equal to 1.
- The throughput capacity of Internet traffic exchange nodes $N_{MSK\text{-}IX}$ or ($N_{MSK\text{-}IX} + N_{IXes}$) corresponds to 30 channels, i.e., 300 Gbit·s.
- The availability factor K_G for a 1,000 km long channel is 0.95.
- The probability of finding content outside exchange nodes q ranges from 0.05 to 0.15.
- The average size of one message $\overline{V_K} = 12\ MB$.

For clarity, we will consider two options for building a network.

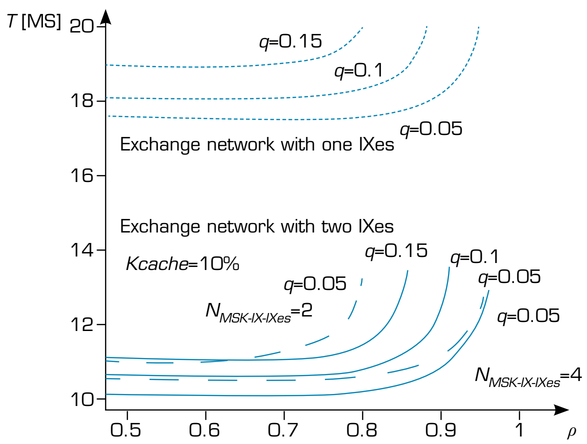
Option 1 – One Internet traffic exchange node: MSK-IX, and the distances of operators of each region to MSK-IX node are $L_1 = 1000$ km, $L_2 = 2000$ km, $L_3 = 3000$ km, $L_4 = 4000$ km, $L_5 = 5000$ km, and $L_6 = 6000$ km.

Option 2 – Two Internet traffic exchange nodes: MSK-IX and IXes, the distance between which is 2,000 km. The operators of the first region exchange traffic with MSK-IX, and the operators from the second to the sixth region exchange Internet traffic through the IXes node, i.e., node IXes is located in the second region. In this case, the distances of the operators of the first region to MSK-IX node are $L_1 = 1{,}000$ km, and the distances of the operators of other regions to node IXes: $L_2 = 0$ km, $L_3 = 1{,}000$ km, $L_4 = 2{,}000$ km, $L_5 = 3{,}000$ km, *and* $L_6 = 4{,}000$ km.

We assume that the update traffic of cache servers between nodes varies from 1 to 10% of the amount of traffic (caching coefficient K_{cache}) circulating in the network. The distribution of the total capacity (bandwidth) of the exchange nodes is proportional to the incoming load per each node. This bandwidth distribution rule is rational, but not optimal due to the non-linearity of the probabilistic-temporal characteristics of information exchange on the bandwidth of nodes, and is accepted only for simplification (this dependence should be proportional to the square root of the load [Kleinrock 1975]). We also assume that if one of the operator's communication channels fails, its traffic is directed to the exchange node through any of the communication channels of another operator in this region. Such an assumption, of course, does not correspond to reality, but it does not affect the qualitative results of a comparative analysis of the two options.

The calculation results are presented below in Figs. 4–7, while the comparison of options was given with the same number of communication channels for each option in the information exchange system $N = 24$.

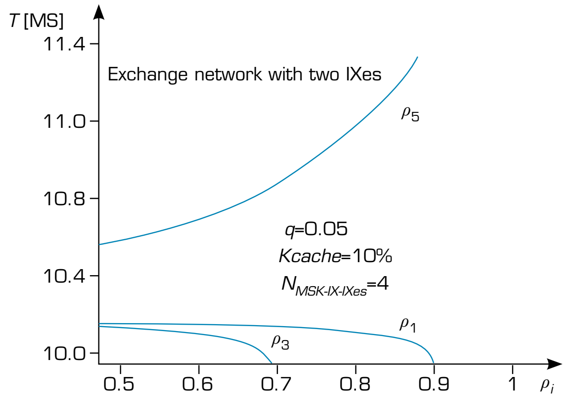
Figure 4 shows the dependencies of the average network delay of information transmission T when the load of communication channels ρ_i changes from 0.5 to 0.95 with a uniform increase in the load of all channels and different values of the number of channels between $N_{MSK\text{–}IX\text{-}IXes}$ traffic exchange nodes (solid line: $N_{MSK\text{–}IX\text{-}IXes} = 4$, dotted line: $N_{MSK\text{–}IX\text{-}IXes} = 2$) and in Fig. 5 with a significantly uneven load on communication channels from operators in different regions.



Source: Elaborated by the authors.

Figure 4. Average network delay with uniform loading of communication channels of operators in different regions.

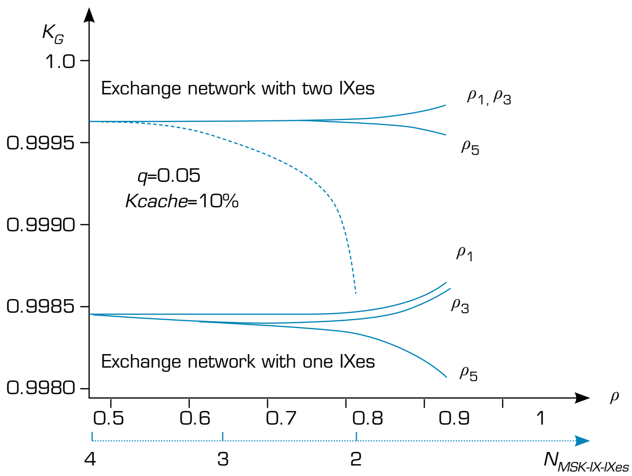
As follows from the above dependencies, the option with two Internet traffic exchange nodes provides almost two times less network delay with a simultaneous increase in network bandwidth of up to 15% even with a decrease in the number of channels between $N_{MSK-IXes-IXes}$ traffic exchange nodes from 4 to 2 (although at high loads, the communication lines (MSK-IX – IXes) are the bottleneck of the network in terms of loading). In Fig. 5, with an increase in load from operators in regions (first and third) close to the Internet traffic exchange nodes, the average network delay decreases, while with an increase in load from operators in distant regions, the delay increases. This is explained by the fact that shorter communication channels from operators in nearby regions contribute a larger share to the network delay, which is calculated as a weighted average proportional to the traffic intensity. Dependencies on this graph show the importance of choosing the location of the exchange node: these nodes should be located in regions with a maximum concentration of Internet traffic. The model developed and presented in the article allows for selecting the most rational location for placing IXes, which minimizes RTD at a given K_G and cost.



Source: Elaborated by the authors.

Figure 5. Average network delay with uneven loading of communication channels of operators in different regions.

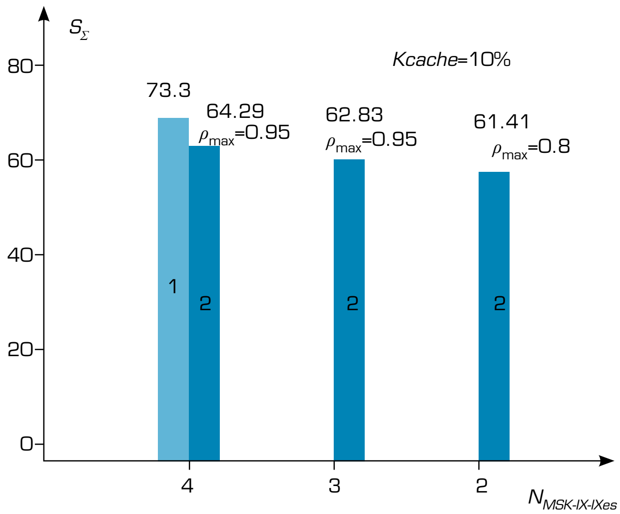
K_G dependencies presented in Fig. 6 show that when using a distributed scheme with two Internet traffic exchange nodes, higher network reliability is provided. The rather large K_G values obtained are explained by the assumption that each operator, in the event of a failure of one of its channels, uses an operable channel of any other operator from its region to communicate with the traffic exchange node. However, in a comparative analysis of different schemes, this assumption is not essential. The same graph shows the dependence of K_G (dashed line) on the change in the number of channels between two IXes, which are designed to pass traffic between the cache servers of these IXes.



Source: Elaborated by the authors.

Figure 6. Network availability factor K_G depending on the load of channels of regional operators ρ and the number of $N_{MSK\text{-}IX\text{ - }IXes}$ channels between nodes IXes.

Fig. 7 shows the values of the network cost S_{Σ} when varying the throughput (number of channels: $N_{MSK-IXes\text{ - }IXes}$) between nodes. The obtained results show that the cost of implementing a distributed network with two Internet traffic exchange nodes can be even 15% lower than for a network with one node. At the same time, as mentioned above, in this case, the network delay is simultaneously reduced and the reliability of the network is increased. This reduction in the cost of the exchange network in the implementation of a distributed network makes it possible to compensate for the costs of owners of Internet traffic exchange nodes for the creation of a second node IXes by slightly increasing tariffs for operators connected to IXes. However, the main thing is that at the same time all operators exchanging through IXes turn out to benefit economically by offsetting this increased tariff by a more significant reduction in the cost of rent for access channels to IXes due to their shorter length. Thus, the implementation of a distributed network option with several, in this case with two IXes, allows all participants in the exchange of Internet traffic (owners of traffic exchange nodes and regional telecom operators) to receive not only economic benefits, but also improve the quality of services provided in the regions, reducing delays and improving service reliability.



Source: Elaborated by the authors.

Figure 7. Cost of Internet traffic exchange network, where 1 is an exchange network with one IX, 2 is an exchange network with two IXes.

DISCUSSION

The developed mathematical models make it possible to compare the performance indicators of alternative options for building Internet traffic exchange networks and determine the rational values of their main parameters. These mathematical models of networks can be detailed to the required level, particularly through more accurate mathematical models of IXes nodes and methods for calculating network reliability. Additionally, to obtain more accurate estimates of network cost indicators, it is possible to use other approaches to estimating the cost of a communication channel based on its length than Eq. 35. The approach proposed in the article for calculating the characteristics of Internet traffic exchange networks can be generalized to an arbitrary number of IXes.

As for the problem of minimizing network delays under restrictions on network cost when choosing the bandwidth of communication channels, it should be solved by considering the results of Kleinrock (1975).

The choice of the Poisson model for input traffic is determined by the purpose of this article: to development of an analytical model that allows comparing alternative architecture options for an Internet traffic exchange network, selecting its optimal structure (determining the optimal number of Internet traffic exchange nodes: IX), and obtaining quantitative estimates of selected performance indicators. To solve this class of problems, the Poisson model of input traffic is traditionally used. It allows for determining the specified characteristics in an explicit analytical form. In the works of Millán *et al.* (2021) and Park and Willinger (2000), based on experimental traffic data, it is shown that in the backbone channels of real Internet traffic exchange networks, a more accurate model is the model of self-similar Internet traffic. However, this model is most effectively used (mainly through simulation models) in solving problems related to choosing the performance of switches/routers, for accurately assessing QoS (RTD and jitter delays), choosing the volume of storage devices of switches/routers (calculating the probability of packet loss), and dealing with explosive traffic (cyber-attacks: DDoS), high load and overload. It is clear that the required quantitative values of throughput/performance and storage capacity in this case, of course, will be higher/greater than when using the Poisson model.

This article was carried out within the framework of a grant and represents the result of the first stage: the development of an analytical model for organizing the exchange of Internet traffic in geographically distributed communication networks. The second stage is the collection of statistical data on the structure of Internet traffic in Moscow and a several other Russian IXes, and the third is the development of a simulation model considering the obtained data. Therefore, the authors plan to publish the results at the end of the third stage, which will complement the results of analytical modeling.

CONCLUSION

The results of the analysis allow for the following conclusions and recommendations:

- The efficiency of organizing Internet traffic exchange networks as a part of SAGSIN significantly depends on the number of IXes, the topology of backbone communication networks, the capacity and reliability of access channels to IXes, and the cost of renting communication channels.
- An increase in the number of IXes leads to a decrease in RTD, an increase in SLA, and a reduction in the costs of telecom operators for renting communication channels to IXes, but it increases the costs for IXes node owners to create infrastructure. Obviously, there is an optimal number of IXes nodes that maximizes the given performance indicators of the Internet traffic exchange network.
- The problem of choosing the number of IXes is similar to the problem of choosing the optimal location of distribution warehouses, which uses linear programming methods, combinatorial methods, dynamic programming methods, set theory, and vector optimization. However, the mathematical models developed using these methods are quite abstract, and the solutions are obtained in an implicit form.
- As a mathematical model of an Internet traffic exchange network, a model of a queuing network is proposed, in which nodes and communication channels are generally multichannel queuing systems.
- Performance indicators when comparing various options for constructing a network with one or more IXes include the average value of network delay, the throughput of the communication network and exchange nodes, the reliability of channels and the entire network, and its cost.
- When comparing alternative options, minimizing the average delay, maximizing the throughput of the communication network and its reliability, and subject to restrictions on the cost of the communication network are used as efficiency criteria.
- The article shows that for sufficiently large, geographically extended Internet traffic exchange networks, as well as for multi-SCN, a network with one IX node is not optimal.
- The article proves that an Internet exchange network with multiple IXes provides lower latency, higher availability, and lower cost.
- The article shows that a network with several IXes generally allows all participants (IXes owners and regional telecom operators – IXes participants and users) to receive economic benefits and improve the quality of the services provided.
- The presented mathematical model of an Internet traffic exchange network makes it possible to determine the optimal network topology based on one or more basic parameters.
- A rational organizational option for building distributed IXes networks is to combine the ownership of IXes and backbone communication networks into one entity, as implemented by Google and Yandex, for example.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTIONS

Conceptualization: Chechin G and Kolesnichenko V; **Methodology:** Chechin G and Kolesnichenko V; **Research:** Chechin G and Kolesnichenko V; **Software:** Chechin G and Kolesnichenko V; **Data curation:** Chechin G and Kolesnichenko V; **Formal analysis:** Chechin G and Kolesnichenko V; **Validation:** Chechin G and Kolesnichenko V; **Visualization:** Chechin G and Kolesnichenko V; **Resources:** Chechin G and Kolesnichenko V; **Acquisition of funding:** Chechin G and Kolesnichenko V; **Project administration:** Chechin G and Kolesnichenko V; **Supervision:** Chechin G and Kolesnichenko V; **Writing - Preparation of original draft:** Chechin G and Kolesnichenko V; **Writing - Proofreading and editing:** Chechin G and Kolesnichenko V; **Final approval:** Kolesnichenko V.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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