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RESEARCH ARTICLE

Analysis of the structural reliability of communication networks supporting protective switching mechanisms for one protected section and one backup section

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Abstract

Objectives. The service level agreement is an important tool used in building reasonable relations between subscribers and operators of telecommunication networks. This includes the quality of services provided. One key component is reliability as assessed by the availability factor. The most suitable model for assessing the reliability of the service provided is a random graph model based on the service contour. This is the set of technical resources involved in the provision of this service. In this formulation, the assessment of the reliability of the service is based on the reliability of elements which constitute the telecommunications network (graph), nodes (vertices) and communication lines (edges). At the same time, the availability factors of nodes and lines are determined by the design features of the distribution environment, as well as the technical means used to organize them. The purpose of this work is to develop an approach to analyzing the reliability of telecommunication networks which support protective switching mechanisms for one protected and one backup sections.

Methods. The following methods are used: theory of random graphs, matrices, probabilities and computer modeling.

Results. The elements of the route, both basic and reserving, are divided into three groups. The first indicates permanent unchangeable parts of the paths, the second group identifies the reserved sections, and the third group indicates the reserving sections. At the same time, each of the reserved and reserving sections is formed on the basis of specified preferences. They are usually aimed at increasing the resulting reliability, although other rules may be used. In the case of protective switching schemes for one protected section and one backup sections, a variant of forming routes used for further calculations of the reliability indicator is shown.

Conclusions. Using the example of a backbone network, the study shows that the use of protective switching mechanisms for the case of one required transmission route demonstrates a significant increase in reliability, with the exception of the use of protective switching in sections. This is primarily due to the topology features of the network under consideration.

Keywords: communication network, graph, connectivity probability, protective switching, reliability, service, availability factor

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НАУЧНАЯ СТАТЬЯ

Анализ структурной надежности сетей связи с механизмами защитного переключения для одного защищаемого и одного резервного участков

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Резюме
Цели. Известно, что соглашение об уровне обслуживания является важным инструментом выстраивания разумных отношений между абонентами и операторами телекоммуникационных сетей, в т.ч. в части качества предоставляемых услуг, одной из составляющих которого является надежность, оцениваемая коэффициентом готовности. Наиболее подходящей моделью для оценки надежности предоставляемой услуги оказывается случайная графовая модель, строящаяся на основе контура обслуживания – совокупности технических средств, участвующих в оказании данной услуги. В данной постановке оценка надежности услуги отталкивается от надежности составляющих телекоммуникационную сеть (граф) элементов – узлов (вершин) и линий связи (ребер). При этом коэффициенты готовности узлов и линий определяются конструктивными особенностями среды распространения и организующих их технических средств. Целью работы является разработка подхода к анализу надежности телекоммуникационных сетей, поддерживающих механизмы защитного переключения для одного защищаемого и одного резервного участков, позволяющего на основе компьютерного моделирования проводить сравнение подобных механизмов.
Методы. Использованы методы теории случайных графов, матриц, вероятностей и компьютерного моделирования.
Результаты. Предложено разбивать на три группы элементы маршрута (как основные, так и резервирующие): первая группа указывает на постоянные неизменяемые части путей, вторая – идентифицирует резервируемые участки, а третья группа указывает на резервирующие участки. При этом каждый из резервируемых и резервирующих участков формируется на основе заданных предпочтений и обычно направлен на увеличение результирующей надежности, хотя возможно использование и других правил. Для схем защитного переключения для одного защищаемого и одного резервного участков показан вариант формирования маршрутов, используемых для дальнейших расчетов показателя надежности путем компьютерного моделирования.
Выводы. На примере магистральной сети путем компьютерного моделирования показано, что использование механизмов защитного переключения для случая одного требуемого маршрута передачи демонстрирует существенный рост надежности, за исключением применения защитного переключения на участках, что связано, прежде всего, с особенностями топологии рассматриваемой сети.

Ключевые слова: сеть связи, граф, вероятность связности, защитное переключение, надежность, услуга, коэффициент готовности

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INTRODUCTION

The service level agreement (SLA) is an important tool for building reasonable relations between subscribers and telecommunication network operators [1]. At the same time, both international recommendations and Russian standards suggest its use in the information and telecommunication technology sectors. In accordance with this agreement, both parties reach a certain understanding of the service provided, as well as its quality, responsibility, priority and other factors.

The basic structure of an SLA for any communication service includes nine sections. The section containing service level information necessarily contains information on the service quality indicators, as well as the values of the indicators guaranteed to the subscriber by the operator (GOST R 55389-2012[1]). The most significant of these are the indicators which characterize the readiness of the service. Both direct indicators, for example, downtime or MTBF, and indirect indicators, such as availability factor, which is the most commonly used reliability indicator can be used. Sometimes simpler deterministic indicators are used which characterize the connectivity of an equivalent graph modeling the original telecommunication network or even the service [2].

The choice of this as a key indicator is because it simply and clearly eliminates misunderstandings between users and operators. It is specified in the form of a share (percentage) of the service uptime at the corresponding access point to the service.

The values of the availability factor guaranteed by the operator, as well as other indicators, are established on the basis of existing federal and industry documents. For example, there are standards which regulate local telephone services (GOST R 53727-2009[2]), tone frequency channels,[3] network and line paths.[4,5] However, the situation concerning dynamically developing modern telecommunication services is not entirely satisfactory. One usually has to be content with the legislative values of Russian or foreign telecom operators, formalized on the basis of the experience of operation of their telecommunication networks (Rec. E. 860[6]). An example would be the International Telecommunication Union recommendations for optical transport networks (Rec. G. 8201[7]) or multimedia services (Rec. G. 1010[8]).

In such a situation, it is extremely important for the service provider to estimate the availability factor of the service requested by the user. The main obstacle is the large measurement interval required to obtain reliable experimental estimates, increasing significantly as availability factors increase. The application of calculation relations, enabling us to calculate such estimates on the basis of a certain set of initial data available to the telecom operator, allows us to analyze its capabilities from the point of view of end-user requests made in advance.

[1] GOST R 55389-2012. National Standard of the Russian Federation. *System of National Standards for quality of telecommunication services. Service Level Agreement* (*SLA*). Moscow: Standartinform; 2019. 12 p. (in Russ.).

[2] GOST R 53727-2009. National Standard of the Russian Federation. *Quality of service "Local telephone communication." Quality indices*. Moscow: Standartinform; 2011. 11 p. (in Russ.).

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[5] *Regulations for electrical parameters of network paths of main and intra-area primary networks*. Part II. Approved by the Ministry of Communications of the Russian Federation 08.01.1997. Moscow: MK-Polygraph; 1996. 168 p. (in Russ.).

[6] Rec. E. 860. *Framework of a service level agreement*. Geneva: ITU-T; 2003. 30 p. https://www.itu.int/rec/T-REC-E.860-200206-I/en. Accessed February 26, 2024.

[7] Rec. G. 8201. *Error performance parameters and objectives for multi-operator international paths within optical transport networks*. Geneva: ITU-T; 2012. 24 p. https://www.itu.int/rec/T-REC-G.8201. Accessed February 26, 2024.

[8] Rec. G. 1010. *End-user multimedia QoS categories*. Geneva: ITU-T; 2002. 18 p. https://www.itu.int/rec/T-REC-G.1010/en. Accessed February 26, 2024.

1. RELIABILITY OF THE NETWORK AND ITS COMPONENTS

The most suitable model for assessing the reliability of the service provided is a random graph model [3], based on the service loop. This is set of technical resources involved in the provision of this service [1, 4]. In this formulation, the service reliability assessment is clearly based on the reliability of the elements constituting the telecommunication network (graph): nodes (vertices) and communication lines (edges) [5]. In this case, methods which require specified subgraphs, for example, paths [6] or sections [7], in the structure of the initial graph are often used.

The availability factors of nodes and lines are determined by the design features of the propagation environment and their organizing technical facilities (Rec. G. 911[9]) [8]. However, the operator usually does not have a detailed description of such features, so simplified models are used.

Applied network equipment, such as optical cross-connectors and I/O multiplexers, consists of a significant number of different elements. Each is characterized by its own MTBF and recovery time (Rec. G. 911) [9]. MTBF T_0 of network equipment is expressed as a dimension of time or number of failures per unit time, usually taken as 10^9 h, or approximately 114155 years. The average recovery time T_r, on the other hand, is expressed in hours. The availability factor corresponds to the probability of connectivity p of the corresponding node or line: $p = \frac{T_r}{T_0}$.

Link failures can be caused either by optical cable failure, or by failures of optical amplifiers or WDM (wavelength division multiplexing—multiplexing with wavelength division multiplexing, spectral multiplexing) systems. A commonly accepted assumption is that failures of individual fibers in an optical cable occur simultaneously, since they are most often caused by digging faults leading to failure of all fibers at once. For a cable, the mean time-to-failure T_0 is given as a measure of the burst length corresponding to the average cable length d_0 exposed to a single cut per year. This condition can be explained by the increasing probability of a cable break as its length d increases. Longer sections potentially have more opportunities of being damaged by external influences. The average MTBF of an optical cable, expressed in hours, is determined by the expression [9]

$$T_0 = 8760\frac{d_0}{d}.$$

The mean time T_r of cable restoration includes time of fault localization, access to the cable, damage repair and commissioning, including testing of information exchange quality.

A list of average MTBF and recovery times for the most commonly used network equipment is presented in [9]. To some extent, these values are too highly averaged and may differ among equipment manufacturers. They may change even more so over time due to the improvement of the element base. Nevertheless, their application is justified from the point of view not of obtaining the absolute values of the calculated reliability indicators of telecommunication networks, but as a tool for comparing the mechanisms of fault tolerance due to the proximity of the indicators to real typical values. The MTBF for modern equipment is often even lower than the data provided [10]. The reason, apparently, is the complication of the electronic components base.

Next we consider a bidirectional communication line connecting two nodes by cable segments interspersed with optical amplifiers at a distance of about 100 km. The communication line is clearly operable when all its constituent elements are ready. Assuming statistical independence of their failures, the line availability factor p_{line} can be calculated using the formula:

$$p_{\text{line}}(d) = (1 - 6.088 \cdot 10^{-6} d) \cdot 0.999952^{\left\lfloor \frac{d}{100} \right\rfloor} \cdot 0.999988^2. \quad (1)$$

2. SAFETY SWITCHING MECHANISMS

The availability factor of an individual communication line is calculated simply using the model of serial connection of elements as a basis. However, in real telecommunication networks characterized by alternative routes, the situation is much more complicated [11]. In this case, protective switching mechanisms [12], or backup circuits, play an important role in the final reliability of connections.

This paper considers the impact of telecommunication network characteristics on final reliability from the position of the most commonly used indicator: availability factor. Issues relating to the efficiency of switching to backup channels require further clarification [13]. The methods of protection switching (protection) for one main route (Rec. G. 808[10]) [14] are considered as basic mechanisms of fault tolerance provision. There is also a protection switching architecture with one protected

[9] Rec. G. 911. *Parameters and calculation methodologies for reliability and availability of fibre optic systems* (*Previously CCITT Recommendation*). Geneva: ITU-T; 1994. 39 p. https://www.itu.int/rec/T-REC-G.911/en. Accessed February 26, 2024.

[10] Rec. G. 808. *Terms and definitions for network protection and restoration*. Amendment 1. 2018–03. Geneva: ITU-T; 2018. 20 p. https://www.itu.int/rec/T-REC-G.808/en. Accessed February 26, 2024.

section and one backup section (1 : 1 or 1 + 1), as well as six varieties of protected sections of network elements: line, node, route, segment, ring, p-cycle [9]. Each of the varieties has its own properties from the point of view of technical realization. However, from the point of view of reliability analysis based on random graphs, it is sufficient to consider the protected section as a set of vertices and edges of the graph, the use of which is permitted only on the main route. In this case, the use of rings or p-cycles is also reduced to such types of backup by simple transformations.

3. ARCHITECTURE OF INFORMATION TRANSMISSION ROUTES

Path elements, both basic and reserving, can be characterized in three groups (Fig. 1). The first indicates permanent unchangeable parts of the paths and is defined as a vector $\mathbf{s}=\{s_i\}_{i=\overline{1,l+v}}$ of the initial graph elements, where s_i = 1, if ith graph element (edge or vertex) is contained in the given path, and s_i = 0, if not. l is the number of edges in the graph v is the number of vertices in the graph. The second group identifies the reserved sections and is represented in the form of a matrix $\mathbf{S}=\{s_{i,j}\}_{\substack{i=\overline{1,l+v},\\ j=\overline{1,n}}}$ each column of which is equivalent to one of the n where similarly $s_{i,j}$ = 1, if the ith element is contained in the jth path, and $s_{i,j}$ = 0, if not. The third group indicates the reserving sections, and it is written in the form of a matrix $\mathbf{T}=\{t_{i,j}\}_{\substack{i=\overline{1,l+v},\\ j=\overline{1,m}}}$, each column of which is equivalent to one of the m reserving sections. Here likewise $t_{i,j}$ = 1, if the ith element is contained in the jth path, and $t_{i,j}$ = 0, if not. Each backup and reserving section is formed on the basis of given preferences, and is usually aimed at increasing the resulting reliability, Other rules may also be used.

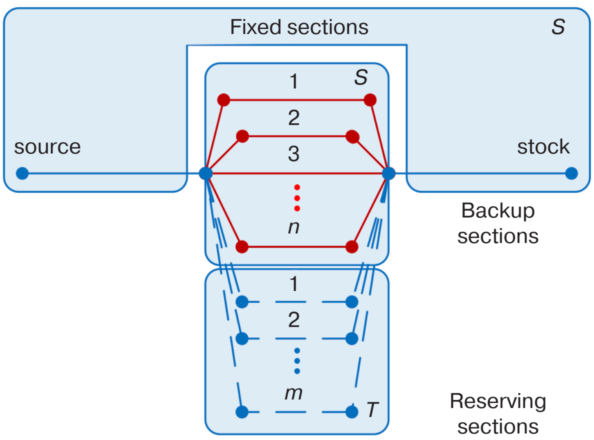

Fig. 1. Architecture of information transmission routes with protection switching mechanisms

Thus, in the general case for protective switching architectures it is reasonable to consider n basic routes of transmission of information as a basis. They are usually defined in the form of simple circuits with independent protected sections with maximum availability factors. Protected sections have maximum availability factors. Then the matrix of backup sections is selected on the basis of the maximum value of the availability factor between the given elements of the initial graph, taking into account their independence and that they are not included in the fixed part of the route

$$\mathbf{S}^{\langle 1\rangle}=\left\{\mathbf{W}^{\langle j\rangle}:\max\left[\mathbf{s}+\mathbf{W}^{\langle j\rangle}\right]=1,\max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}\right\},$$

$$\mathbf{S}^{\langle i\rangle}=\left\{\mathbf{W}^{\langle j\rangle}:\max\left[\mathbf{s}+\operatorname{sign}(\mathbf{S1}_{i-1})+\mathbf{W}^{\langle j\rangle}\right]=1,\right.$$
$$\left.\max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}\right\},\ i=\overline{2,n},$$

where $\mathbf{W}=\{w_{i,j}\}_{\substack{i=\overline{1,l+v},\\ j=\overline{1,s}}}$ is the matrix of paths between the source and the drain of backup sections; $w_{i,j}$ = 1, if the ith element is contained in the jth path and $w_{i,j}$ = 0 if it is not contained; $\mathbf{p}=\{p_i\}_{i=\overline{1,l+v}}$ is the vector of probabilities of connectivity (operability) of edges and vertices; p_i is the probability of connectivity (availability factor) of the ith element.

Here, each column $\mathbf{S}^{\langle i\rangle}$ of the reserved sites matrix is formed from a column $\mathbf{W}^{\langle j\rangle}$ of the path matrix. This column at the same time does not have repeated elements in the previous main paths already used. This can be verified by the general condition $\max\left[\mathbf{s}+\operatorname{sign}(\mathbf{S1}_{i-1}+\mathbf{W}^{\langle j\rangle}\right]$, and has the maximum connectivity probability (availability factor) among the possible alternative paths. It can be expressed as $\max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}$.

Directly, the main routes are represented as a path matrix $\mathbf{R}$:

$$\mathbf{R}=\mathbf{s1}_n^{\mathrm{T}}+\mathbf{S}.$$

Similarly, in a general case, m routes containing backup sections are defined in the form of simple chains with independent backup, wherein reserving sections have a maximum availability factor. Then the matrix of redundant sections is chosen based on the maximum value of the availability factor between the given elements of the initial graph. This takes into account their independence and that they are not included in the fixed part of the route and backup sections

$$\mathbf{T}^{\langle 1\rangle}=\left\{\mathbf{W}^{\langle j\rangle}:\max\left[\operatorname{sign}(\mathbf{R1}_n)+\mathbf{W}^{\langle j\rangle}\right]=1,\ \max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}\right\},$$

$$\mathbf{T}^{\langle i\rangle}=\left\{\mathbf{W}^{\langle j\rangle}:\max\left[\operatorname{sign}(\mathbf{R1}_n)+\operatorname{sign}(\mathbf{T1}_{i-1})+\mathbf{W}^{\langle j\rangle}\right]=1,\ \max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}\right\},\ i=\overline{2,m}.$$

Here, each column $\mathbf{T}^{\langle i\rangle}$ of the reserving sections matrix is formed from a column $\mathbf{W}^{\langle j\rangle}$ of the path matrix which simultaneously has no repeated elements in the already used previous main and reserve paths. This can be checked by the general condition $\max\left[\mathbf{s}+\operatorname{sign}(\mathbf{S1}_{i-1}+\mathbf{W}^{\langle j\rangle}\right]$, and has the maximum connectivity probability (availability factor) of the possible alternative paths given by the expression $\max_{j=\overline{1,s}}\prod_{i=1}^{l+v}p_i w_{i,j}$.

The backup routes themselves are also represented as a path matrix **U**:

$$\mathbf{U}=\mathbf{s}\mathbf{1}_m^{\mathrm{T}}+\mathbf{T}.$$

4. PROTECTIVE SWITCHING ARCHITECTURE FOR ONE PROTECTED AND ONE BACKUP SECTION

For one protected section and one redundant section (1 + 1 or 1 : 1 schemes) (Fig. 2), the original main path is supplemented by a backup path with the same source and stock, with no elements of the protected section of the main path. It also has the maximum availability factor from all possible options. Thus, the matrices of backup **S** and reserving **T** sections are reduced into vectors. The simple circuit matrix **R** contains two columns, the first of which $\mathbf{R}^{\langle 1\rangle}$ points to the primary path, and the second one $\mathbf{R}^{\langle 2\rangle}$ to the reserving path:

$$\mathbf{R}^{\langle 1\rangle}=\mathbf{s}+\mathbf{S},$$

$$\mathbf{R}^{\langle 2\rangle}=\mathbf{s}+\mathbf{T}.$$

5. EXAMPLE OF ANALYZING THE RELIABILITY OF THE MAIN NETWORK

The cable structure of the backbone network of southern Russia (Fig. 3) is available on the official site of the International Telecommunication Union.[11]

[11] https://bbmaps.itu.int/bbmaps/. Accessed February 26, 2024.

Fig. 3 also shows the numbered equivalent graph G(12, 21). The onnectivity probability according to GOST R 53111–2008[12] can be interpreted as the availability factor and characterizes reliability.

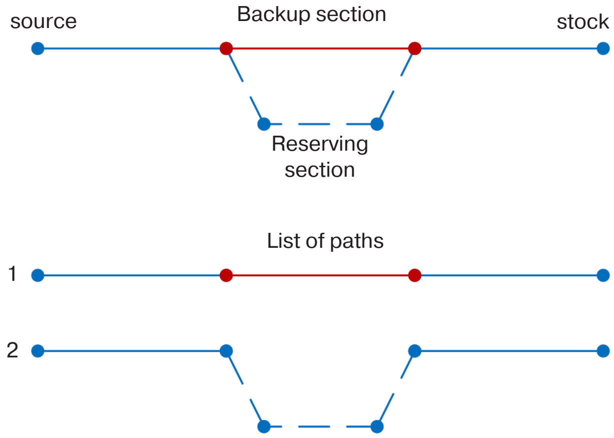

Fig. 2. Protective switching architecture for one protected and one backup section and list of paths

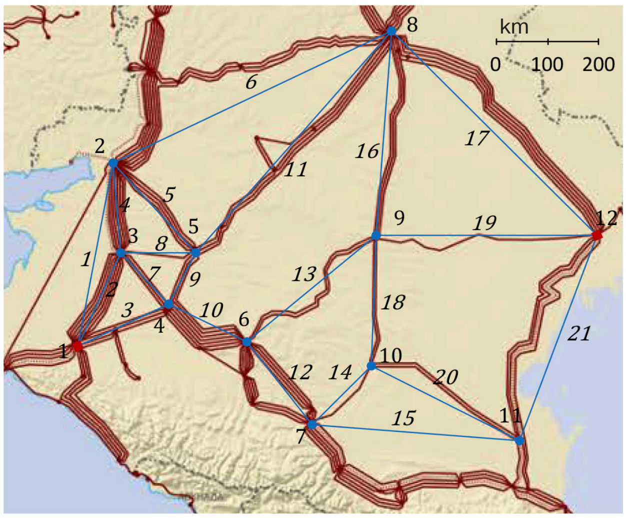

Fig. 3. Cable structure of the main network in the south of Russia

There is assumed to be at least one cross-connector or I/O multiplexer on the node, working for all valid communication directions. It has an average MTBF of 10^5 h and mean recovery time of 6 h [9]. So the availability factor of any unit is

$$p_{\text{vertex}}=1-\frac{6}{10^5}=0.99994.$$

Availability factor p_1 of individual links is calculated for fiber-optic transmission systems based on the length

[12] GOST R 53111–2008. National Standard of the Russian Federation. *Stability of functioning of the public communications network. Requirements and check methods*. Moscow: Standartinform; 2009. 16 p. (in Russ.).

Table 1. Reliability parameters of the communication lines

Line No.	Length d_l, km	Availability factor p_l	Line No.	Length d_l, km	Availability factor p_l	Line No.	Length d_l, km	Availability factor p_l
1	375	0.99755	8	150	0.99901	15	410	0.99729
2	200	0.99866	9	115	0.99923	16	400	0.99735
3	200	0.99866	10	110	0.99926	17	565	0.9963
4	175	0.99886	11	575	0.99624	18	265	0.99827
5	250	0.99836	12	225	0.99851	19	430	0.99717
6	600	0.99604	13	325	0.99785	20	325	0.99785
7	140	0.99908	14	165	0.99892	21	440	0.99711

calculated from the geographic coordinates of the cities between which the link is deployed.

Calculated on the basis of (1) parameters of the communication lines are given in the Table 1.

All types of protected sections for protective switching mechanisms for one protected section and one standby section (1 + 1 or 1 : 1 schemes) are considered. The results of calculations obtained by computer modeling in accordance with the multivariable inversion method [15] are given in Table 2.

Table 2. Network reliability parameters without backup and with protective switching

Section	Availability factor
Line	0.99966
Unit	0.99984
Segment	0.99284
Route	0.99981
Ring	0.99985
p-cycle	0.99986
Without backup	0.99266

The use of protection switching mechanisms for a single required transmission route (Table 2) shows a significant increase in reliability. The exception is protection switching on segments. This is primarily due to the specific nature of the topology of the considered network. Thus, the most reliable route 1–4–6–9–9–12 contains three backup segments 1–4–6, 4–6–9 and 6–9–12, each of which has a reserving path intersecting with the reserving paths of neighboring segments, significantly reducing the protective properties of the route.

CONCLUSIONS

The proposed method of analyzing the reliability of telecommunication networks supporting protective switching mechanisms divides elements of the main and backup routes into three groups. The first includes permanent unchangeable parts of the paths, the second—backup, and the third—reserving sections. Such representation allows the effects of duplication of elements in different routes to be taken into account. As a consequence, this eliminates errors in estimating the availability factor when compared with methods using the assumption of independence of information transmission paths.

Based on the example of a mainline network by computer modeling, the study shows that the use of protective switching mechanisms for one required transmission route demonstrates a significant increase in reliability. The exception is protective switching on segments. This is primarily due to the specific topology of the considered network which prevents the formation of segments completely independent of other paths.

Authors' contributions

K.A. Batenkov—the idea of the study, consultations on conducting all stages of the study.

A.B. Fokin—developing the approach to the analysis of the structural reliability of communication networks with protective switching mechanisms, computer modeling.

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