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RESEARCH ARTICLE

Analytical method for analyzing message transmission processes in FDDI networks for digital substations

Alexander S. Leontyev,
Dmitry V. Zhmatov @

MIREA – Russian Technological University, Moscow, 119454 Russia
@ Corresponding author, e-mail: zhmatov@mirea.ru

Abstract
Objectives. To develop analytical approaches for the evaluation of probability-time characteristics and fiber distributed data interface (FDDI) network performance with the marker access method, thus enabling communication processes for digital electrical substations to be automated.
Methods. The authors used theory reliability methods, random process theory, mass maintenance theory, the Laplace–Stieltjes transformation for inferring functional equations and the probability-time characteristics calculation for the information transfer processes with the occurring failures.
Results. We conducted a numerical study of packet transfer processes between central processing stations in the FDDI network. We considered the processes of discrete information exchange between electronic devices in the system of electrical digital substations. These included the main technological operations and electrical digital substations operator performed when preparing reports. We described the different modes of operation, both for the individual electrical digital substation and for the system. The authors calculated node loading dependencies, FDDI network performance and temporal characteristics of the packet transfer processes on the incoming message flow intensity and the transmission medium reliability. We conducted a functional analysis of the FDDI networks on two fiber-optic rings which form the main and redundant path of data transfer between the network nodes, significantly increasing network resiliency. The objective of the study was to analyze the information transfer processes in FDDI networks with an accent on ensuring the transmission medium reliability.
Conclusions. We were able to establish the existence of the critical operating network region, which leads to a sharp increase in node load and temporal characteristics, while performance reaches its maximum value and then sharply decreases. We propose the exchange of discrete messages to reflect the electronic devices state and information messages of operator between various remotely spaced electrical digital substation with the FDDI fiber-optic network.

Keywords: digital substations, FDDI networks, token access method, models, time characteristics, failures, performance

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НАУЧНАЯ СТАТЬЯ

Аналитический метод анализа процессов передачи сообщений в оптоволоконных сетях с маркерным доступом для цифровых подстанций

А.С. Леонтьев,
Д.В. Жматов @

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ *Автор для переписки, e-mail: zhmatov@mirea.ru*

Резюме
Цели. Цель работы – разработка аналитических методов оценки вероятностно-временных характеристик и производительности оптоволоконной FDDI-сети (fiber distributed data interface) с маркерным методом доступа, позволяющих автоматизировать процессы передачи сообщений для цифровых электроподстанций.
Методы. Использованы методы теории надежности, теории случайных процессов и теории массового обслуживания, преобразование Лапласа – Стилтьеса для вывода функциональных уравнений.
Результаты. Проведено численное исследование процессов передачи пакетов между электрическими цифровыми подстанциями (ЦПС) в оптоволоконной сети FDDI. Рассмотрены процессы обмена дискретной информацией между электронными устройствами в системе электрических ЦПС, включая основные технологические операции, выполняемые персоналом системы ЦПС при подготовке отчетов, характеризующих различные режимы работы как отдельных ЦПС, так и всей системы в целом. Получены зависимости загрузки узлов, производительности FDDI-сети и временных характеристик процессов передачи пакетов от интенсивности входных потоков сообщений и надежности передающей среды. Проведен анализ функционирования FDDI-сетей, построенных на основе двух оптоволоконных колец, которые образуют основной и резервный пути передачи данных между узлами сети, что значительно повышает отказоустойчивость таких сетей. Задача исследования включала анализ процессов передачи информации в сетях FDDI с акцентом на обеспечение надежности передающей среды.
Выводы. Выявлено, что существует критическая область функционирования сети, при достижении которой наблюдается резкое увеличение загрузки узлов и временных характеристик, в то время как производительность достигает максимального значения и затем резко снижается. Предложено осуществлять обмен дискретными сообщениями, отражающими состояние электронных устройств, и информационными сообщениями персонала между различными дистанционно разнесенными ЦПС с использованием оптоволоконной сети FDDI.

Ключевые слова: цифровые подстанции, FDDI-сети, маркерный метод доступа, модели, временные характеристики, отказы, производительность

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INTRODUCTION

The digital substation (DSS) is a type of electrical substation where all monitoring, analysis and control processes are performed in a single digital format. The main link for data transmission in such substations is a local area network (LAN) based on Ethernet technology.

One of the main functions of DSS is the exchange of discrete information between digital electronic devices, including voltage and current transformers [1–4]. The GOOSE (generic object-oriented substation event) data transfer protocol described in IEC 61850[1] standard [5–7]. GOOSE model provides a fast mechanism for transmitting events (e.g., commands and warnings) and is used to shut down, start devices, and record alarm events. During the design phase, the utilization and bandwidth of the data transmission paths must be taken into account. The size of a GOOSE message ranges from 573 to 830 bytes. When the message includes 64 discrete signals, the size of a GOOSE message including service information (28–30 bytes, including preamble, sender and receiver addresses, cyclic control code, control fields, limiters, status field) is 1 Kbyte. In this regard, when modeling the exchange of discrete signals between different DSS connected to the fiber distributed data interface (FDDI) network, the synchronous traffic in the network is a GOOSE message of 1 Kbyte or 8 kbits in size. In order to accelerate the development process and improve the quality of the DSS system, methods need to be proposed to analyze the efficiency of the applied information technologies, in particular, standard technologies for preparing information and analytical reports by personnel. The creation of mathematical models to describe the main stages and schemes of report preparation enables the selection of system components for the realization of different modes of operation of both individual DSS and the whole system to be automated on the basis of multivariate analysis. The functioning of individual DSS is based on the use of Fast Ethernet LAN, while the FDDI fiber-optic network is used for the interaction of different DSS.

The main functional tasks performed by DSS system personnel on a daily basis when preparing reports describing various modes of operation of both individual DSS and the entire system include fact-based information retrieval, contextual information retrieval, frequency analysis by report attributes, sorting, clustering, and semantic analysis.

[1] GOST R IEC 61850-5-2011. National Standard of the Russian Federation. *Communication networks and systems in substations*. Part 5. Communication requirements for functions and device models. Moscow: Standartinform, 2020 (in Russ.). The standard describes data flow formats, types of information, rules for describing the elements of an energy object, and a set of rules for organizing an event-based data transfer protocol.

1. METHODOLOGY FOR RECEIVING A MESSAGE TO DSS

The maximum length of lines between DSS is 200 km, provided that the ring does not exceed 100 km. The maximum number of double connection nodes is limited and is 500. According to the IEC 61850 standard [1–3], there are two options for exchanging GOOSE messages between power facilities.

The first option (Fig. 1) relies on tunneling technology. In this context, a broadband Ethernet channel is formed between the objects, through which GOOSE messages are transmitted using network equipment.

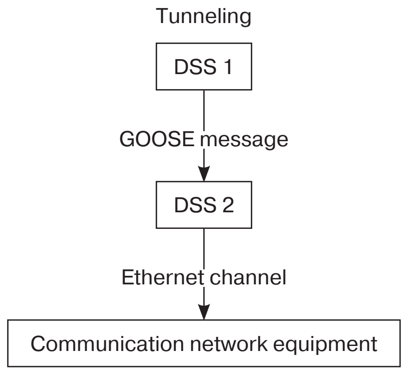

Fig. 1. Tunneling technology for the transmission of GOOSE messages between DSS components

The second scenario, shown in Fig. 2, involves the use of a gateway. In this scenario, an alarm and command device is used to exchange GOOSE messages between objects. The alarm and command devices convert discrete signals from GOOSE messages into coded analog or digital signals for the safe transmission of relay protection commands over the DSS channel. At the receiving end of the alarm and command transmitter, GOOSE messages are generated from the encoded signals received via the channel.

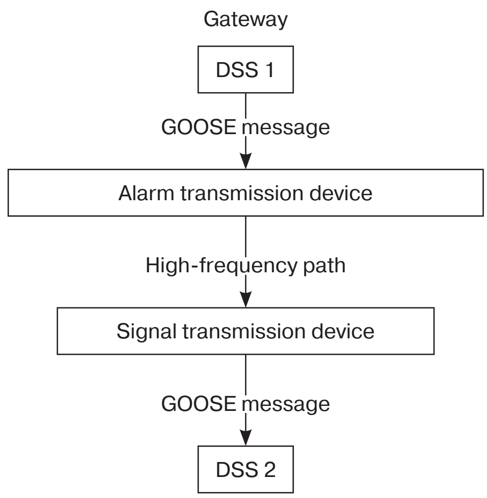

Fig. 2. Use of alarm transmission devices

In order to transmit GOOSE messages using tunneling, digital channels between substations are required. They can be organized by means of digital industrial communication networks or dedicated fiber optic channels. However, the organization of reliable digital high-frequency channels for GOOSE messages is impossible. This is due to the need to transmit relay protection and emergency control commands when short circuits occur on power lines [2–4].

FDDI fiber optic networks can be interconnected with a DSS, in order to enable efficient data transmission in digital power transmission networks. Digital substations can use FDDI networks to exchange data between various devices in the power system, such as monitoring and control systems, security systems, load management systems, and other devices requiring fast and reliable data transmission. Connecting FDDI networks to DSS enables the use of fiber rings to transmit large amounts of data at high speed and reliability, provide high bandwidth, fault tolerance and low latency data transmission. This is especially important for critical power transmission systems.

2. TASK STATEMENT OF THE PROBLEM OF ANALYTICAL STUDY OF THE FDDI NETWORK

When analyzing the performance of FDDI networks, it is paramount that methods, models and algorithms be created which take into account the characteristics of data transmission in these networks, including possible failures.

Simulation methods to determine the temporal characteristics of computer systems and networks under failure conditions are inefficient [8]. Currently known analytical methods are usually applicable to the analysis of local structures and, as a rule, are focused on the analysis of either the time characteristics of local systems with regard to reliability [9–11], or reliability indicators of computer systems and networks [12–14].

Let us consider the problem formulation and analytical model for estimating the time characteristics and performance indicators of FDDI networks with fiber optic rings taking into account the reliability of the transmission medium and limitations on the data transmission time. This approach and its implementation expand the scope of application of the methodology for the study of data transmission processes in local networks using analytical methods [15, 16].

The main indicators in this context are probabilistic and temporal characteristics which are highly dependent on failures of the transmission medium.

A detailed formulation of the problems of research into the probabilistic-temporal characteristics and performance of Ethernet-type LANs and LAN with the token access method, as well as analytical methods of their solution were first developed by A.S. Leontyev and published in 2001 in [15]. The general formulation of the problem of research of probabilistic-temporal characteristics and performance of FDDI networks corresponds to the methodology described in [15]. It can be formulated as follows: **to determine the probabilistic-temporal characteristics of packet transmission, the load of nodes and transmission medium, as well as to evaluate the performance of fiber-optic FDDI networks at a given bandwidth and reliability of the transmission medium, the structure and number of nodes of the FDDI network, streams of transmitted information and limitations on the time of packet transmission.**

The selected performance metric is the total intensity of the flow served in time. The solution of the problem is based on the assumption that the flows λ_n, $n=\overline{1,N}$ entering the network for service and the failures of the transmission medium are of Poisson distribution. It is envisioned that the input to the node is via an accumulator with unlimited capacity. As shown in [15], these assumptions are justified in the development of system modes of operation of the local network. The accuracy of the results obtained with their help is acceptable for engineering calculations.

3. DEVELOPMENT OF MATHEMATICAL APPARATUS FOR FDDI NETWORK RESEARCH

Let us number the nodes of the network in the order of polling, and use the index n to denote the station (node) of the FDDI network. Let N be the number of nodes in the network, λ_n is the intensity of packet flow to the nth node. The average packet transmission time from one node to the neighboring node is determined by the ratio:

$$X^{(1)} = \frac{L_{\text{pac}}}{C},$$

wherein L_{pac} is the length of the packet including the length of the marker; C is the throughput of the transmitting medium.

Obviously, the average interval $Z^{(1)}$ between two consecutive polls of a node is equal to:

$$Z^{(1)} = \sum_{n=1}^{N}\left\{\rho_n X^{(1)} + (1-\rho_n)\frac{L_{\text{m}}}{C}\right\},\quad n=\overline{1,N}, \tag{1}$$

wherein ρ_n is the load of the nth load, L_{m} is the marker length.

In steady-state mode:

$$\lambda_n Z^{(1)} = \rho_n. \tag{2}$$

From (1) and (2) we obtain:

$$\lambda_n \sum_{n=1}^{N} \left\{ \rho_n X^{(1)} + (1-\rho_n)\frac{L_\text{m}}{C} \right\} = \rho_n. \quad (3)$$

The system of equations (3) is an inhomogeneous system of linear algebraic equations with regard to ρ_n.

$$\rho_n = \frac{\lambda_n N \frac{L_\text{m}}{C}}{1 - \sum_{k=1}^{N} \lambda_k \left(X^{(1)} - \frac{L_\text{m}}{C} \right)}, \ n = \overline{1, N}, \quad (4)$$

λ_k is the maximum number of packets in a node; k is the maximum number of nodes.

By comparing (2) and (4), we obtain:

$$Z^{(1)} = \frac{N \frac{L_\text{m}}{C}}{1 - \sum_{k=1}^{N} \lambda_k \left(X^{(1)} - \frac{L_\text{m}}{C} \right)}. \quad (5)$$

Formulas (4) and (5) determine the utilization of the network nodes and the average polling cycle of the nodes under the conditions of reliable operation.

Functional equations for determining the cycle of the network with token access method taking into account occurring failures have the following form:

$$Z_\text{f}^*(s) = Z^*(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s)), \quad (6)$$

$$Y_\text{f}^*(s) = F_\text{f}^*(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s)), \quad (7)$$

$$Z_\text{f}^*(s) = \int_0^\infty \text{e}^{-st} dZ_\text{f}(t), \quad Y_\text{f}^*(s) = \int_0^\infty \text{e}^{-st} dY_\text{f}(t),$$

$$Z^*(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s)) = \int_0^\infty \text{e}^{-(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s))t} dZ(t),$$

$$F_\text{f}^*(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s)) = \int_0^\infty \text{e}^{-(\lambda_\text{f} + s - \lambda_\text{f} Y_\text{f}^*(s))t} dF(t),$$

wherein $Z_\text{f}(t)$ is the distribution function (DF) of the network cycle taking into account failures, $Z(t)$ is the DF of the network cycle under conditions of reliable operation, $F_\text{f}(t)$ is the DF of the transmission medium recovery time after failures, $Y_\text{f}(t)$ is the DF of the transmission medium occupancy period after failures, and s is the complex parameter of the DF of the network cycle taking into account failures.

Functional Eqs. (6) and (7) can be obtained using the catastrophe method [9], in accordance with the technique described in [15]. Differentiating (6) and (7) by s, we obtain:

$$Y_\text{f}^{(1)} = \frac{F_\text{f}^{(1)}}{1 - \lambda_\text{f} F_\text{f}^{(1)}}, \quad (8)$$

$$Z_\text{f}^{(1)} = \frac{Z^{(1)}}{1 - \lambda_\text{f} F_\text{f}^{(1)}}. \quad (9)$$

The Laplace–Stieltjes transform of the DF of packet transmission time taking into account the occurring failures $X_\text{f}^*(s)$ is defined using the following functional equation:

$$X_\text{f}^*(s) = X^*(s + \lambda_\text{f}) + \frac{\lambda_\text{f}}{s + \lambda_\text{f}} (1 - X^*(s + \lambda_\text{f})) F_\text{f}^*(s) X_\text{f}^*(s), \quad (10)$$

wherein $X^*(s + \lambda_\text{f}) = \int_0^\infty \text{e}^{-(s + \lambda_\text{f})t} dX(t)$, $X(t)$ is the DF of packet transmission time over the transmitting medium under conditions of reliable operation.

Functional Eq. (10) is easily obtained by using the catastrophe method [9].

Moments $V_n^{(1)}, V_n^{(2)}$ of the service time DF of a packet arriving at the free nth node are defined by the expressions:

$$V_n^{(1)} = X_\text{f}^{(1)} + W_{n|\xi_n=1}^{(1)}, \quad V_n^{(2)} = X_\text{f}^{(2)} + 2W_{n|\xi_n=1}^{(1)} X_\text{f}^{(1)} + W_{n|\xi_n=1}^{(2)}, \quad (11)$$

wherein ξ_n is the number of packets in node n; $X_\text{f}^{(1)}, X_\text{f}^{(2)}$ are the DF moments $X_\text{f}(t)$; $W_{n|\xi_n=1}^{(1)}$, $W_{n|\xi_n=1}^{(2)}$ are the 1st and 2nd DF moments of waiting time for the arrival of a token at the nth node at $\xi_n = 1$.

The average waiting time of packets in the queue for service in the nth node of FDDI network $W_n^{(1)}$ is given by the Pollaczek–Khinchine formula [15]:

$$W_n^{(1)} = \frac{1}{2} \cdot \frac{\lambda_n V_n^{(2)}}{1 - \lambda_n V_n^{(1)}}, \quad (12)$$

wherein $V_n^{(1)}$, $V_n^{(2)}$ are defined by the formulas (11).

The average packet delivery time $T_n^{(1)}$ in the network is defined by the expression:

$$T_n^{(1)} = W_n^{(1)} + V_n^{(1)}. \qquad (13)$$

The total intensity of the timely served packet flow (FDDI network performance) is calculated by the formula:

$$\lambda_{\text{tot}} = \sum_{i=1}^{N} \lambda_i P_i, \qquad (14)$$

wherein P_i is the probability of timely delivery of packets arriving to the ith node of the FDDI network, λ_i is the intensity of packets arriving to the ith node of the network.

Analytical relations necessary for estimating the probability P_i of timely delivery of packets arriving at the ith node of the network taking into account emerging failures are presented in [9, 15].

4. SOFTWARE PACKAGE FOR ANALYSIS OF INFORMATION TRANSMISSION PROCESSES IN FDDI NETWORK AND MODELING RESULTS

The authors have developed a set of programs which enable the analytical model considered above to be used in practice, in order to evaluate the efficiency of FDDI network. It can be installed on the FDDI network server for access from workplaces.

Analytical apparatus implemented in the form of this software package enables automated study of the structure and characteristics of FDDI network with two fiber rings, taking into account the reliability of the transmission medium. The screen form of input of initial data and output of modeling results is shown in Fig. 3. The user can enter the input data in the dialog mode using the specified forms.

The calculation results are displayed on the screen as text and in graphic windows. The user can correct the initial data and save the results of calculations in text and graphic files without leaving the modeling system.

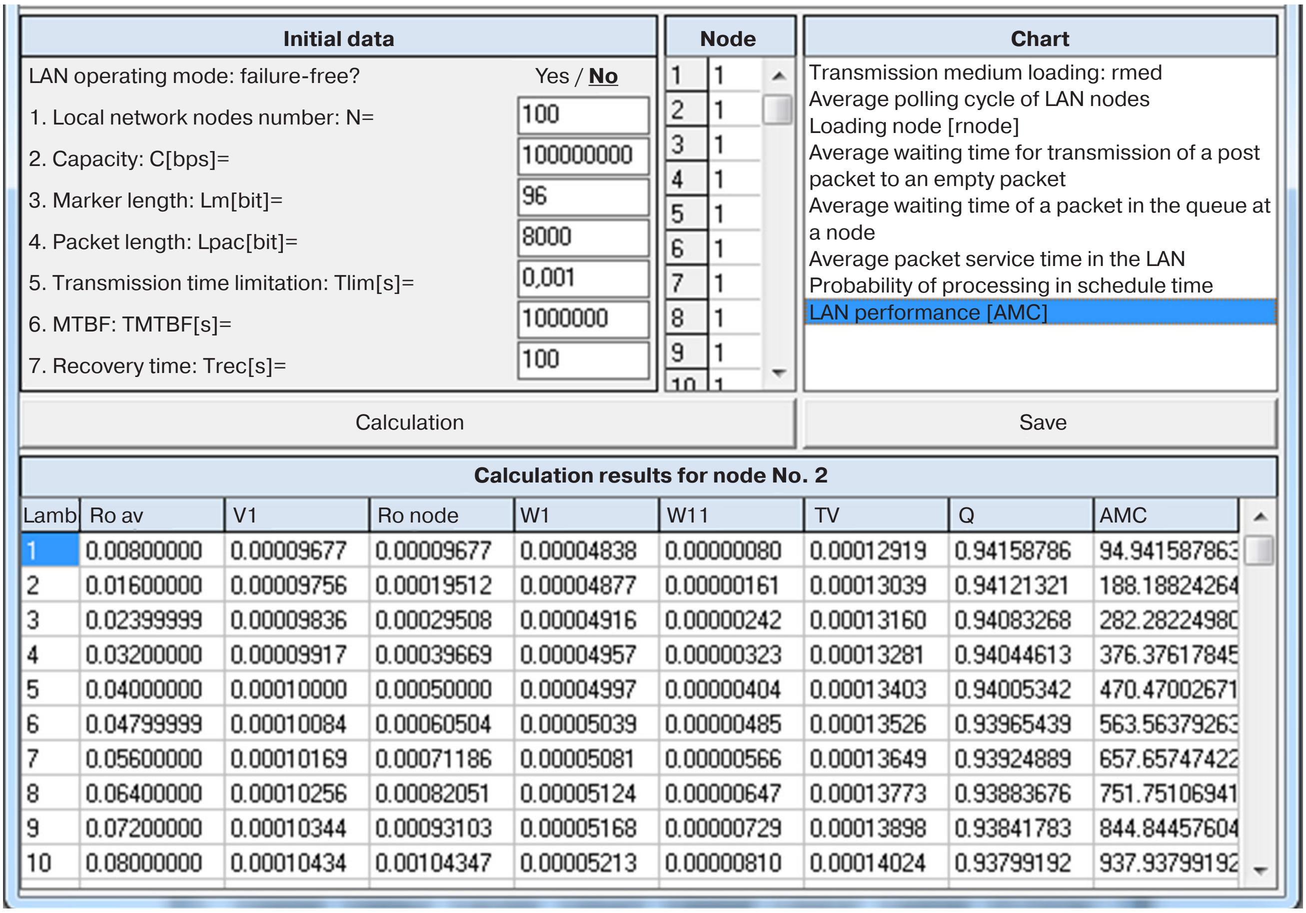

Fig. 3. Screen form for input of initial data and output of modeling results.
AMC—automatic message counting

In order to demonstrate the study of packet delivery processes and performance of fiber optic FDDI networks using the developed analytical method, a simulation of packet transmission is performed. The following initial data were selected for modeling:

- type of transmission medium is two fiber optic rings;
- type of node distribution in the network is random;
- number of nodes in the network $N = 100$;
- bandwidth 100 Mbps;
- MTBF of the transmission medium 100000–1000000 s;
- average recovery time after failure 100 s;
- marker length 96 bits;
- directive time 1 ms;
- synchronous packet length (discrete GOOSE message) 8 kbits;
- intensity of arrival of synchronous packets (discrete GOOSE messages in DSS system) is the same in all nodes of FDDI network (variable parameter).

It should be noted that the group of programs developed enables modeling to be performed at different intensity of the packets arriving to the network nodes for service.

Results of calculations of the probability-time characteristics, performance, node utilization and transmission medium of the FDDI network of the DSS system with given initial data under load variation are presented in Figs. 4–10.

In an FDDI network, packet delivery time depends on the time waiting for transmission in the queue at the network nodes and the time of packet transmission. Therefore, the parameters of information processing in the network should be chosen in such a way that in the whole range of changes in the intensity of the flows of processed packets there are no bottlenecks in the system, i.e., overloads of individual nodes and the transmission medium. In a balanced system, the load of the transmission medium and the load of the nodes when the load increases should be close to each other. As the failure rate decreases and the number of nodes decreases for a given transmission medium capacity, the length of transmitted packets should increase, in such a way that the network is balanced when the load increases.

It should be noted that with an increasing failure rate in FDDI network and increasing number of nodes for a given network throughput to balance the network in the whole range of load changes, and in order to obtain optimal performance, the length of transmitted information packets needs to be reduced, since it will reduce the probability of distortion.

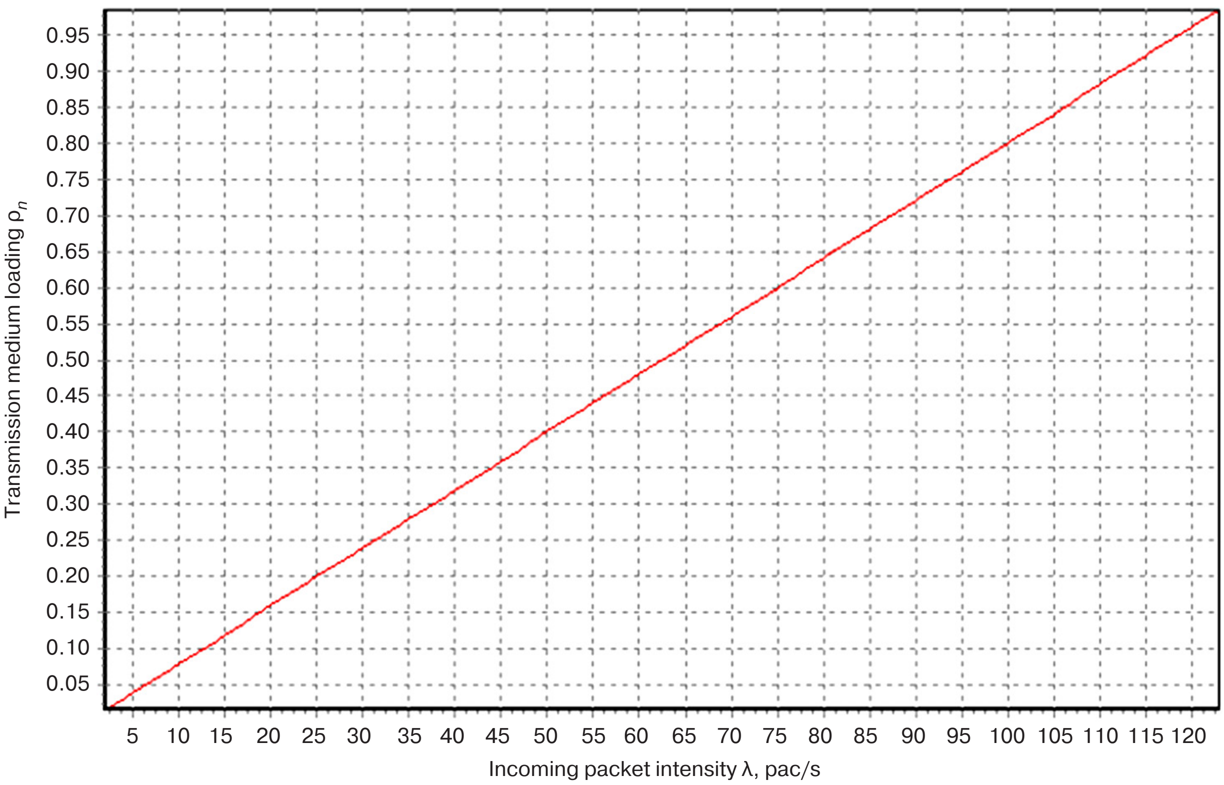

Fig. 4. Dependence of transmission medium load of fiber-optic FDDI network of DSS system on the intensity of synchronous packets arrival to the nodes

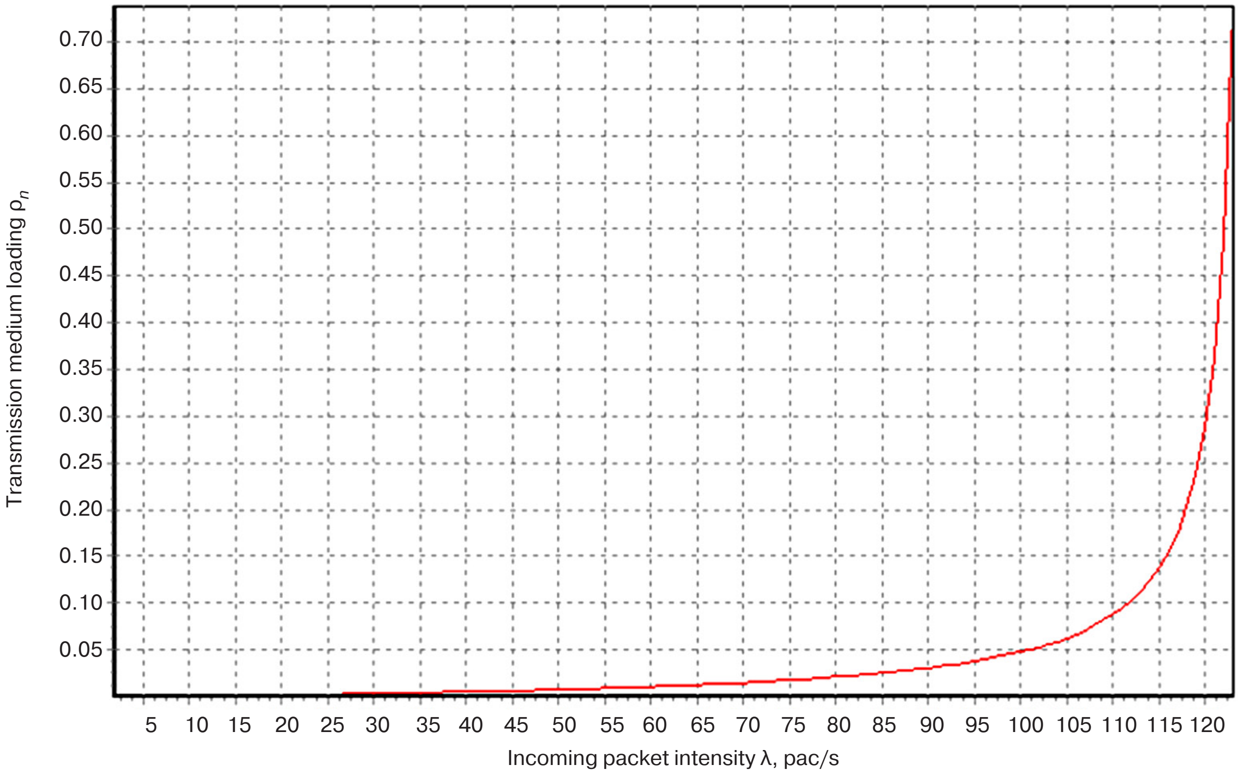

Fig. 5. Dependence of FDDI network node utilization of the DSS system on the intensity of synchronous packets arrival to the nodes

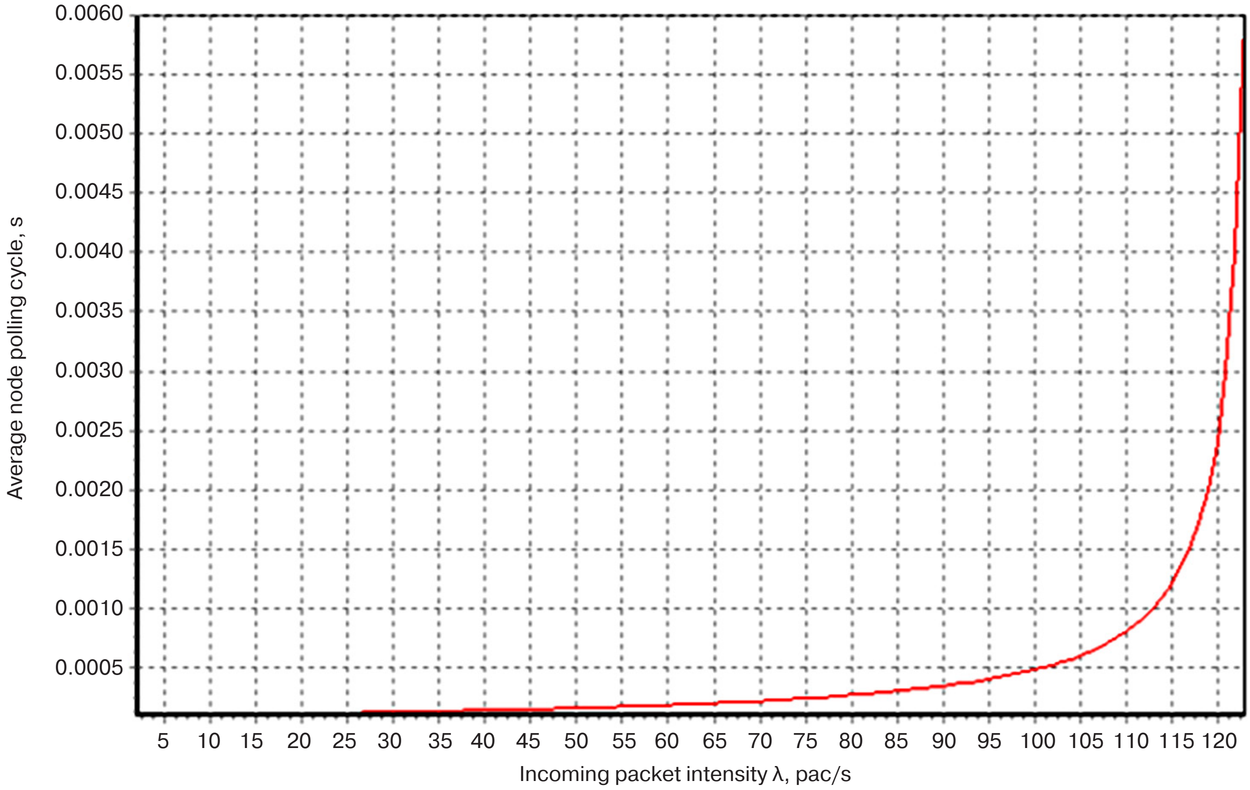

Fig. 6. Dependence of the average polling cycle of the nodes of the FDDI network of the DSS system on the intensity of arrival of synchronous packets to the nodes

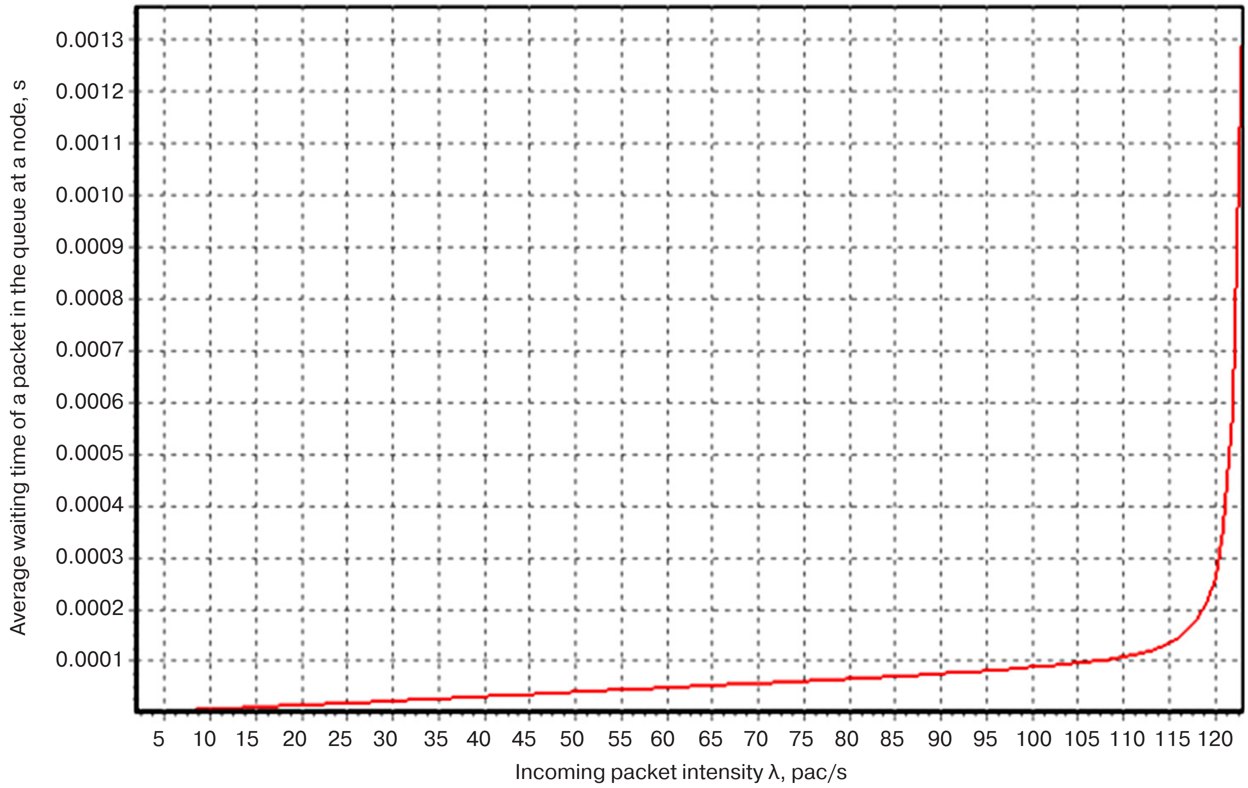

Fig. 7. Dependence of the waiting time for the beginning of synchronous packet transmission in the queue at the node of the FDDI network of the DSS system on the intensity of synchronous packets arrival

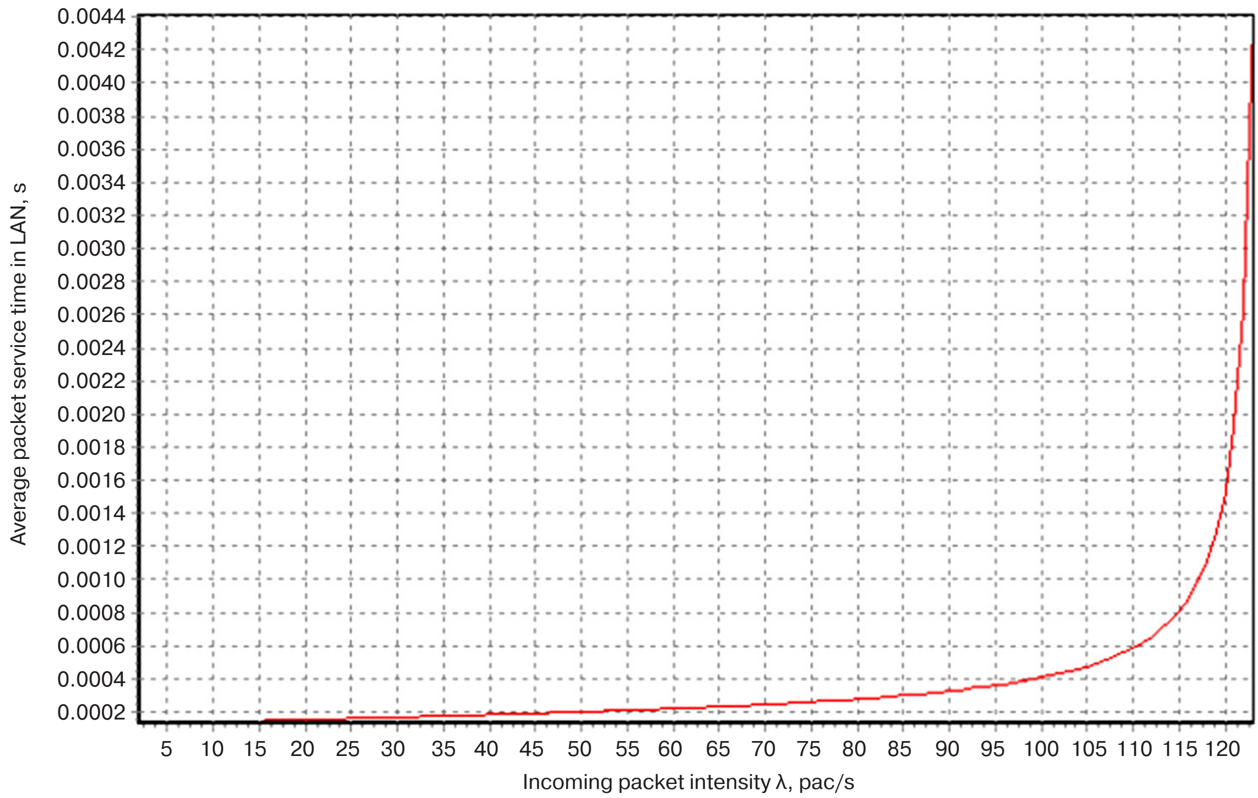

Fig. 8. Dependence of the average service time of synchronous packets in the FDDI network of the DSS system on the intensity of arrival of synchronous packets to the nodes

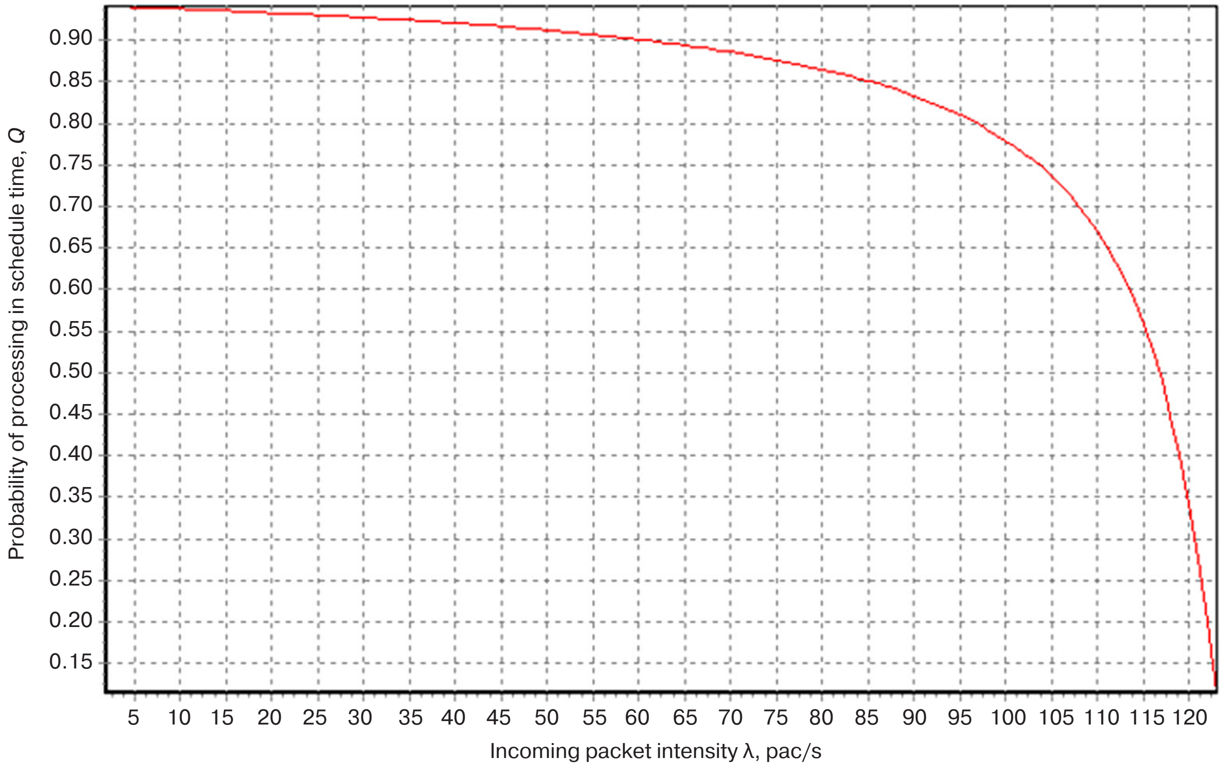

Fig. 9. Dependence of the probability of synchronous packets processing in the given directive terms in the FDDI network of the DSS system on the intensity of synchronous packets receipt

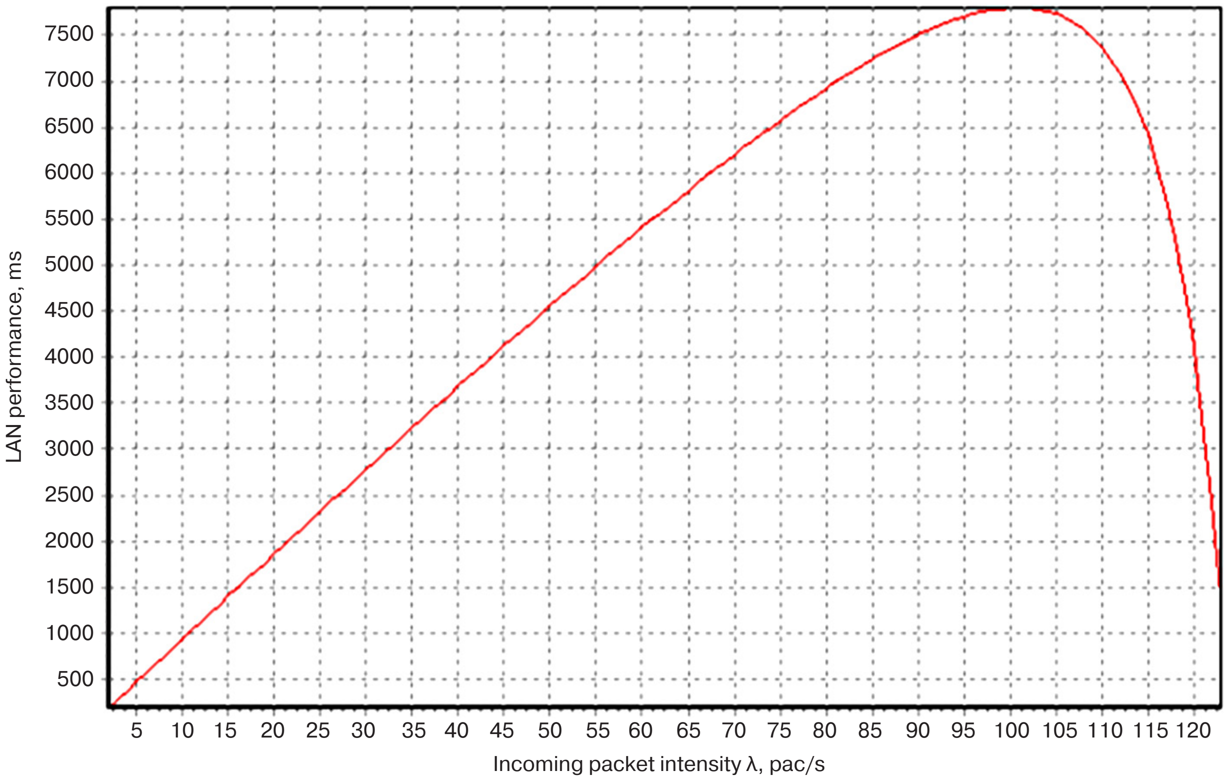

Fig. 10. Dependence of performance, total timely served flow of synchronous packets in FDDI network of the DSS system on the intensity of arrival of synchronous packets

As can be seen from the graphs (Figs. 4–9), as the intensity of packet flows served in the FDDI network increases, the node utilization, node polling cycle and timing characteristics increase, while the network performance (the total timely served packet flow in the network) reaches the maximum value and begins to fall sharply. As the failure rate of the transmission medium increases, the area of abrupt change of FDDI network characteristics shifts to the side of lower utilization.

Consequently, certain modes need to be provided for the operation in FDDI networks of a set of separated DSS when exchanging synchronous packets (GOOSE messages and packets transmitting synchronized parameters of vector measurements for DSS) between different DSS. The objective must be to prevent reaching the area of sharp changes in FDDI network performance, i.e., the need to control the intensity of input flows and limit their growth.

Specific recommendations on the selection of parameters and modes of operation of FDDI network used for information exchange in a distributed system of DSS can be obtained by conducting multivariate analytical calculations using a set of programs implementing the analytical method for the study of fiber-optic FDDI networks, while taking into account the reliability of the transmission medium.

CONCLUSIONS

The study developed a standard technological scheme of report preparation by DSS dispatchers. The authors propose the use of a fault-tolerant FDDI network with two fiber optic rings as a telecommunication component for information exchange between different nodes in the system of remote DSS. Discrete GOOSE messages form a synchronous flow of FDDI network packets, while information messages arising during the performance of basic technological operations in the preparation of reports by dispatchers of the central station do not form such a flow.

The study looked at aspects of development of the analytical models for the estimation of probabilistic-temporal characteristics and performance of FDDI networks with fiber optic rings taking into account possible failures in the transmission medium. The problem was posed and an analytical method was developed, in order to assess the performance of FDDI networks taking into account the reliability of the transmission medium, thus extending the scope of analytical approaches.

The conclusion which can be drawn based on this research is that a mechanism must be implemented to control packet flows entering the network, in order to ensure the efficient operation of FDDI networks. Thus, controlling the intensity of incoming flows and limiting their growth becomes an important aspect of ensuring the efficient operation of the network.

Based on the analytical method developed herein, a set of programs for studying the processes of information transmission in FDDI networks was created. This software enables multivariate analysis of different modes of operation of FDDI networks used for data transmission between remote DSS.

The study also established analytical expressions for estimating node and transmission medium utilization, average packet dwell time in the network, probability of timely packet service and performance. Aspects of FDDI network operation and transmission medium reliability were taken into account when formulating these expressions.

It was found that there is a critical load for FDDI networks at which the network performance reaches a maximum and then decreases sharply. As the failure rate of the transmission medium increases, the critical modes of FDDI network operation shift towards lower loads.

In order to ensure the efficient operation of FDDI networks, the modes of operation need to be regulated in such a way as to avoid reaching critical load at the nodes and in the transmission medium. Controlling the intensity of input flows and limiting their growth are key elements for DSS systems in FDDI networks.

Authors' contribution
All authors equally contributed to the research work.

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About the authors

Alexander S. Leontyev, Cand. Sci. (Eng.), Senior Researcher, Associate Professor, Department of Mathematical Support and Standardization, Institute of Information Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: leontev@mirea.ru. RSCI SPIN-code 5798-9721, https://orcid.org/0000-0003-3673-2468

Dmitry V. Zhmatov, Cand. Sci. (Eng.), Associate Professor, Department of Mathematical Support and Standardization, Institute of Information Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: zhmatov@mirea.ru. Scopus Author ID 56825948100, RSCI SPIN-code 2641-6783, https://orcid.org/0000-0002-7192-2446

Об авторах

Леонтьев Александр Савельевич, к.т.н., старший научный сотрудник, доцент, кафедра математического обеспечения и стандартизации информационных технологий, Институт информационных технологий, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: leontev@mirea.ru. SPIN-код РИНЦ 5798-9721, https://orcid.org/0000-0003-3673-2468

Жматов Дмитрий Владимирович, к.т.н., доцент, кафедра математического обеспечения и стандартизации информационных технологий, Институт информационных технологий, ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: zhmatov@mirea.ru. Scopus Author ID 56825948100, SPIN-код РИНЦ 2641-6783, https://orcid.org/0000-0002-7192-2446

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