Currently, data traffic is growing rapidly, and ensuring optimal network performance and effective data flow management have become the most important tasks. In this context, the quality of network service plays a crucial role in achieving these goals.

This article suggests an approach to solving the problem of efficient service in ISDN. Namely, optimization of resource distribution between channel switching and packet switching subnets in ISDN to calculate optimal quality of service characteristics.

In the process of ISDN design analysis, an optimization problem is compiled, where the evaluation of the packet-switched subnet service is used as an objective function, and the evaluation of the circuit-switched subnet service is used as one of the constraints for this task. To calculate the main characteristics of a packet-switched subnet, the subnet is considered as a service system with a delay.

During the study, the methods of optimal movement of the generalized channel boundary between the subnets of channel switching and packet switching were identified, depending on the data parameters and the state of the integrated network, which made it possible to develop an optimal mathematical model of optimal control of the generalized boundary. To calculate the bandwidth for channel switching and packet switching subnets, an algorithm has been compiled to implement the resulting model and a program in C++ has been compiled.

The study of the generalized boundary and the dynamic redistribution of bandwidth between subnets represents a new approach to network optimization.

The results are based on the use of the classical Erlang formula for systems with service failures and on load distribution plans, which makes it possible to effectively manage the maintenance process in the network

Keywords: circuit switching, packet switching, mathematical model, service quality function, bandwidth, Lagrange method

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DEVELOPMENT OF A MATHEMATICAL MODEL FOR ASSESSING THE QUALITY OF SERVICE ON A PACKET SWITCHING SUBNET

Roza Mukasheva
PhD*
Zhenisgul Rakhmetullina
Corresponding author
PhD*
E-mail: Zhrakhmetullina@ektu.kz
Indira Uvaliyeva
PhD*
Raushan Mukhamedova
Master of Science*
Farida Amenova
PhD
Department Mathematics
S. Amanzholov East Kazakhstan University
30 Gvardeiskoi divisii str., 34, Ust-Kamenogorsk, Republic of Kazakhstan, 070020
*Department «Engineering mathematics»
D. Serikbayev East Kazakhstan Technical University
Protozanov str., 69, Ust-Kamenogorsk, Republic of Kazakhstan, 070004

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1. Introduction

With the development of network technologies and the growth of the volume of transmitted data, ensuring high quality of service in packet switching networks is becoming an essential aspect. Successful operation of such networks requires not only high bandwidth, but also optimal resource management, minimal packet loss, and low transmission delay.

New types of communication networks and new improved services currently being offered, require increasingly sophisticated control functions. The integration of service types inevitably leads to the idea of integrated management, which refers to the possibility of common management of heterogeneous equipment of different manufacturers for more efficient use of all network equipment.

To carry out the exchange of information in a digital network with integrated services, control procedures are required to ensure reliable and correct transmission of flows of circuit-switched and packet-switched subnetworks. In other words, there must be some rules according to which load management occurs internally and externally with respect to channel switching and packet switching subnets. These rules are commonly referred to as flow control procedures. At the same time, internal control includes such procedures as, for example, the choice of routes for transferring loads, their redistribution along the paths, the allocation of bandwidth in the communication channel, etc. The basis of external management includes the procedure for limiting incoming traffic to the subnet, because uncontrolled admission of it can lead to inevitable overloads and blocking of the entire subnet as a whole. Flow control procedures implement a management system for channel switching subnets and packet switching subnets.

One of the problems in the operation of the network is the optimization of information flow control carried out in the dynamic control system, which will certainly affect the quality of network service. The main tasks of the dynamic control system are optimization of routing, which ensures the distribution of information flows, and flow control, aimed at limiting incoming and transit loads in the network.

Therefore, the development of the mathematical model is one of the key tools for assessing and improving the quality of service.

This is also confirmed by modern publications.

The article [1] presents a technique for creating a wireless digital communication network with packet switching, which is capable of transmitting real-time video messages between elements of a complex information and control system. The main focus is on ensuring stable data transmission even with a high probability of network node failures. Network adaptation is carried out at several levels in order to optimize the parameters and functions of network elements, as well as to transform the structure of subnets depending on the situation. To achieve this goal, an aggregative approach to modeling complex technical systems based on a mathematical model is used.

In the article [2], the authors explain that the development of mobile technologies requires the development of more accurate and complex mathematical models for the analysis and optimization of telecommunication networks, algorithms for optimizing design and making managerial decisions.

The article [3] is devoted to the evaluation of the effectiveness of queue dispatching algorithms of modern telecommunication devices by means of simulation modeling. The main purpose of the work is to create a dispatching discipline that meets the requirements of service quality assurance by developing a mathematical model.

In the article [4], a mathematical model for queue dispatching was obtained that allows adjusting the bandwidth for each channel in intelligent Ethernet switches, based on cyclic algorithms. This model made it possible to develop a color hierarchical temporary Petri net that models an adaptive DRR-TSS algorithm of scarce cyclic maintenance with temporary selection of frames in the switch.

The article [5] illustrates an overview of delays in the queue and provides explanations of their impact on various types of networks, such as wireless network, mobile network, SDN, IoT. Also, an overview of various models, effects and their management was made. Mathematical models of queuing, such as Little Theorem, M/M/1, M/M/m, M/G/1, etc., and their impact on the quality of service of various types of networks are discussed in detail.

In the article [6], based on the developed mathematical model, analytical expressions are obtained that allow to evaluate the reliability of the system, the information security coefficient of the functioning of software and hardware, and the average residence time of the traffic packet stream in the nodes of multiservice telecommunication networks.

The article [7] proposes a mathematical model of MTS performance based on the architectural concept of future networks using virtual, channel, information and network resources. Based on the model, a numerical analysis was carried out and a graphical dependence of the maximum network bandwidth on the total number of hardware and software systems and terminal facilities was constructed for a given system load factor.

The following article [8] is devoted to the optimization of the structure of digital telecommunication networks by the criterion of cost reduction across the entire network. A mathematical model has been developed for calculating the cost parameters of digital communication networks. Numerical results of optimization of the structure according to the criterion of given network-wide costs for various network parameters are obtained.

As it is possible to see, research on this topic is necessary to solve important tasks, such as:

1. Optimization of network resources: The mathematical model allows to determine optimal parameters such as buffer sizes, bandwidth of communication channels and data flow management algorithms, which will help to use the available resources of the network more efficiently as well as increasing its throughput.

2. Improving quality of service: Assessing quality of service allows to identify the problem areas and bottlenecks in the network and determine optimal strategies to minimize packet loss, reduce transmission delays, and ensure network stability. This will increase user satisfaction and improve user experience of interacting with the network.

3. Planning and developing new systems: The development of a mathematical model is an essential part of planning and designing new network systems. Its application gives an opportunity to assess the capabilities of the new system before its implementation. Moreover, it helps to make decisions based on scientific evidence, which reduces the risk of unexpected problems while implementing the network.

4. Cost-effectiveness: The implementation of a mathematical model and research helps to optimize costs of deploying, configuring and maintaining a network infrastructure. Defining the optimal parameters and strategies allows to achieve the best quality of service at minimal cost.

5. Enhancing security: A mathematical model can also enhance network security and protect the network from external attacks and unwanted traffic. The model will help to identify vulnerabilities and develop optimal measures to ensure data security.

In such a way, the development of a mathematical model for assessing the quality of service on a packet switching subnetwork is a relevant task that will help to predict the performance of a packet switching subnetwork system, improve the functioning of such networks and provide an optimal user experience.

2. Literature review and problem statement

In the article [9], the authors show that it is possible to ensure the quality of the network by differentiating the bandwidth with a multipath connection, for its implementation using new architectures of hierarchical crossbar switches that provide quality of service (QoS) applications. Also in the work, based on the results obtained, a comparative study of three schedulers was carried out using the Hiperion modeling tool. However, this work mainly offers theoretical solutions and models, rather than specific practical implementations. Moreover, the issues related to deep research of hardware for obtaining estimates of the silicon area that will be required for the average output scheduling algorithm still remain unresolved.

The paper [10] presents a mathematical model for evaluating the quality of service in computer networks. It focuses on a generalized outbound traffic model and provides a methodology for estimating quality of service metrics such as latency, packet loss, and delivery of packets with a given delay. An analytical method for estimating the quality of service in packet switching subnets is widely discussed in paper [11]. The model developed in this paper considers a set of incoming traffic flows and is based on the theory of queuing networks. It takes into account factors such as packet priority, latency, and the probability of packet loss. The paper [12] shows an overview of modelling the quality of service in packet-switched networks with different user requirements. The work considers various aspects related to the provision of quality of service. Nevertheless, papers [9–12] do not address the specific problems of packet switching subnetworks.

Another concept of network planning to improve the quality of service (Quality of Service, QoS) is discussed in paper [13] using the Packet Tracer program. The main problem solved in this paper is to develop the concept of network planning in order to improve QoS. Quality of Service improvement is an essential part of maintaining network systems, as it allows to provide an optimal service and data delivery in a resource-limited environment. However, some problems related to QoS still remain unsolved. For example, the authors of this paper do not take into account the specifics of a particular network, security issues or resource allocation. In [14], the problem of improving the upstream throughput and energy efficiency in the LoRaWAN network was investigated. Improving upstream throughput is important to ensure more reliable and efficient data transfer from IoT devices on the network. The paper proposes the use of the 2-hop LEACH protocol to improve throughput and energy efficiency in the LoRaWAN network. LEACH (Low-Energy Adaptive Clustering Hierarchy) is a protocol that allows to reduce power consumption and increase throughput in an IoT network by organizing nodes into clusters. However, some possible aspects and problems related to LoRaWAN and the LEACH protocol still remain unresolved. For example, the paper does not take into account the specific characteristics of different types of IoT devices, issues related to security and network deployment, or other factors that affect performance and energy efficiency.

The solution of optimization problems of load control is associated with the least difficulties. It is known that increasing the load above a certain value can lead to a loss of operability of the switched network. Routing reduces network congestion loss to a certain extent, but incoming and transit traffic needs to be managed to avoid loss of operability of the circuit-switched subnetwork. The paper [15] proposes a scheme for dynamic flow scheduling using three methods to improve the quality of service of the network: routing with a given flow, deferred redirection, and adaptive redirection. The paper deals with the problems of energy efficiency, load balancing and quality of service in data center networks (Data Center Networks). The proposed AggreFlow mechanism is aimed at optimizing data flows to achieve energy efficiency, load balancing and provide the required quality of service. However, the paper does not provide solutions to the problem of resource management and network management under dynamic load conditions. In the article of the authors [16], a method for managing the quality of network service is proposed. For its implementation, an algorithm has been developed for routing data packets in a network, taking into account the current load of the predicted path, as well as an algorithm for the operation of a billing quality management system in telecommunications networks.

The results obtained by simulation show the effectiveness of the developed method. However, this paper does not consider the problem of bandwidth management and resource sharing in the network. The article [17] considers the issue of improving the quality of a broadband digital network with integrated services. To solve this issue, an iterative method is used, where the flow distribution and load distribution between each pair of nodes are specified by the route matrix and through the path tree, respectively, the excess load of the asynchronous network is calculated during data transmission by the method of circuit switching and packet switching.

In the general case, the choice of the optimality criterion in the algorithms of dynamic control systems is ambiguous. Preference should be given to criteria related to network path bandwidth utilization factors. This means that such routing or flow control solutions are considered optimal, which, when meeting the requirements for the characteristics of information delivery, allow to maximize the bandwidth of the network paths, or to obtain the maximum values of the bandwidth utilization coefficients of the network paths. In the article [18], to improve the efficiency of the network, a method for calculating the flow channel is proposed, which allows creating switching channels in subnetworks with nodal load. Using this method, the probabilistic-temporal characteristics are calculated, in particular, the probabilities of blocking calls between each pair of nodes, and the dependence of these probabilities on the loss of blocking probabilities is proved. However, the authors of this paper do not provide a practical implementation of the proposed mathematical model.

The article [19] considers the optimization problem of flow distribution in a modern multiservice network. The solution of this problem makes it possible to optimally allocate resources so that the loss of user requests is minimal. The model development is based on the principles used in routing and flow control problems, as well as the system approach. In the article [20], the authors carried out a simple intuitive overview of the theory of effective bandwidth for high-speed digital networks using the theory of large deviations and the Laplace integration method. The calculations of the functions of the effective bandwidth, the distribution of this bandwidth are also carried out. The paper presents a methodology for calculating the effective throughput that can be used to effectively control and manage bandwidth in multi-mode networks. However, the work does not solve the problem of managing the load balance and optimizing routing in the network.

The article [21], asynchronous data transmission on circuit-switched and packet-switched subnets of a broadband digital network with integration of services using data flow bypasses is studied. For this purpose, a mathematical model is described, a method is obtained, and the uniqueness of the solution of the system of equations that determines the value of the nodal load relative to the probability of losses in communication channels using bypass directions of the network is proved. But this paper does not consider specific asynchronous network protocols. It offers a general approach and methods that may be applicable to different protocols, but does not discuss their specifics or propose specific algorithms for each protocol. It focuses on load balancing, but does not consider load management strategies such as bandwidth control, prioritization or queuing. The authors of the work [22] consider the influence of reliability on the qualitative parameters of the transport subnetwork in the information and communication system and the probability of losing packets of external traffic messages based on the theory of queuing. They study the relationship between reliability and parameters such as latency, bandwidth, packet loss, and others. It focuses on the study of the influence of reliability on qualitative parameters, but does not discuss specific strategies or mechanisms for achieving high reliability and does not consider specific methods or algorithms to ensure the reliability of the system. In the paper [23], the authors explore and propose a mathematical model for analysing and predicting the interests of users of social networks, analysing user behaviour, their preferences, and other factors influencing their interests. The paper does not contain a description of specific solutions for the implementation and practical use of the proposed mathematical model. This may limit the understanding and implementation of the model in real Internet platforms.

Thus, in these articles provide important researches related to improving the quality of service in networks, network efficiency, reliability, user behavior and other aspects.

Solving these problems is impossible without creating a comprehensive mathematical approach to modeling such networks, aimed at researching and analyzing network performance parameters, as well as evaluating customer service characteristics that require the development of new methods and algorithms for customer service in networks.

All this allows to assert that it is advisable to conduct a study aimed at building a mathematical model of optimal control of a generalized digital network boundary with service integration. Such a study will be of practical importance for improving the functioning of digital networks and ensuring a higher quality of service through load balancing and resource optimization in a variety of network scenarios.

3. The aim and objectives of the study

The aim of the study is to construct a mathematical model of optimal control of the generalized boundary of a digital network with integration of services. The implementation of this goal will allow more effective management of the distribution of resources in the network, achieving the best quality of service parameters for a variety of services. In practice, this assumes that it will be possible to adapt and optimize the bandwidth between different types of services in real time, based on current conditions and network requirements.

To achieve this aim, the following objectives are accomplished:

– to develop a method for estimating the average delay time during transmission of the packet switching subnet data stream;

– to investigate and determine the interdependence of the service quality indicators of the channel switching and packet switching subnets and use it in a single task of optimal distribution of the integrated services digital network bandwidth;

– to develop a method for solving the obtained optimization problem;

– to calculate bandwidth for channel switching and packet switching subnets.

4. Materials and methods of research

The object of research of this work is a digital communication network with service integration, consisting of circuit switching and packet switching subnets.

The main idea of this study is that dynamic optimization of bandwidth allocation between the circuit switching subnet and the packet switching subnet in an integrated communication network contributes to achieving the best quality of service characteristics in conditions of diverse loads and requirements.

To implement this idea, a digital network with integration of services is considered, based on pulse-code modulation systems with temporary compaction, consisting of hybrid nodes of switching and integrated group tracts (IGT) connecting them. The network integrates two switching modes: circuit switching mode and packet switching mode, where the transmission of one part of the pulse-code modulation cycle is carried out in circuit switching mode, and the other in packet switching mode. Depending on the load level and the situation on the integrated network, the network management system will move the threshold in one direction or another, redistributing the bandwidth of the pulse-code modulation cycle between messages transmitted in circuit switching or packet switching modes.

Splitting the bandwidth of each IGT into circuit switching and packet switching areas leads to splitting the entire network into two subnets: circuit switching subnet and packet switching subnet. At the same time, only communication lines undergo the actual division into two areas, and the channel-forming, switching and other equipment of switching nodes is divided into two areas conditionally.

Each hybrid network switching node receives the values of the load intensities of the circuit switching and packet switching subnets, whose distribution plans for all IGTs are determined by traditional methods of adaptive routing. These methods allow the distribution of the bandwidth of the circuit switching and packet switching subnets between call streams and data separately within each of the subnets. The redistribution of network bandwidth between the circuit switching and packet switching subnets cannot be performed independently, since moving the IGT border increases the bandwidth of one subnet by reducing the bandwidth of the other.

At the same time, the packet switching subnet functioning as part of the ISDN is represented by a queuing system with waiting, the subnet communication channel is represented as a single-device model of the queuing system. This system is characterized by the average time of packet delivery to the destination node.

The average packet delay time in the packet switching subnet is selected as the criterion of service quality of the packet switching subnet. The classical Erlang formula is used to calculate the probability of channel occupancy in the IGT. To minimize the average packet delay time in the packet switching subnet, an optimization problem was formulated.

When constructing the mathematical model, the following assumptions were made:

1) the total input streams are assumed to be Poisson;

2) the lengths of service packets, which are connection requests, are determined independently randomly and obey an exponential distribution law.

Various methods could be used to solve optimization problems, such as linear programming, dynamic programming, and other algorithms. In this work, let's use the method of indefinite Lagrange multipliers.

When obtaining theoretical results, research methods were also used in the work, which are based on the theory of computer science, the theory of communication networks, the theory of teletraffic, graph theory, mathematical statistics and combinatorics.

The study used synthetic data reflecting the characteristics of integrated services digital networks. The main parameters of the model, such as the number of nodes, load distribution, traffic intensity and other characteristics, were determined in order to create an adequate digital network model with integrated services.

The C++ programming language was used to implement the algorithm of the mathematical model for calculating the optimal throughput of the ISDN.

All obtained results are confirmed by numerical implementation and computational experiments in solving real test problems.

During the study, the results that include the statistical parameters of the function of quality of services of the circuit switching and packet switching subnets, as well as the throughput for these subnets were obtained.

Validation of the results allows to conclude that the developed models and proposed solutions are applicable to real digital networks with integrated services.

5. Results of the study of the optimal distribution of bandwidth channel resources of the integrated digital network

5. 1. A method for evaluating the quality of service on a packet switching subnet

The quality of service of the circuit switched subnetwork, represented as a service system with explicit losses, is estimated by the probability of refusing to the user of the sending node to establish a connection with the user of the destination node for further exchange of information traffic between them. User requirements for quality of service are determined by the matrix $P=||p_{ij}||$, $V\times V$, i, $j=1, ..., V$, where p_{ij} is the loss probability of the load λ_{ij} on the routes connecting the sending node i with the receiver node j, where λ_{ij} is average intensity of the incoming call flow entering the integrated services digital network from the user of the sending node i and designated for the user at receiver node j. λ_{ij} is called circuit-switched subnetwork input load. It is the average of the incoming load between the respective pairs of nodes during the busiest hour. Since the circuit-switched subnetwork within the integrated services digital network is represented as a service system with explicit losses, the value is $0<p_{ij}<1$, $i, j=1, ..., V$. The input streams for the circuit switched network are given by the matrix $L=||\lambda_{ij}||$, dimensions of which are $V\times V$, $i, j=1, ..., V$.

With a given routing on circuit switching subnets for each integral-group path j the total intensity of input flows λ_j is fixed for circuit switching mode. For each $IGP_{j,}$ $j=1, ..., M$, the total input streams λ_j are assumed to be Poisson, the message lengths of which are subject to an exponential distribution law with average values, respectively $1/\mu_j$. Let $p_j(\lambda_j, m_j)$ be the probability that in the circuit switching mode, when the demand flow intensity arrives at IGP_j all m_j channels will be busy serving previous requirements. This function depends on the intensity of the incoming load and on the number of time channels served by this load and is different for each line j.

The problem of finding the optimal solution for determining the quality of service on a packet switching subnetwork is reduced to considering a packet switching subnetwork as part of an integrated services digital network as a system with unlimited waiting. This approach helps to evaluate the quality of service with a time delay in the transmission of a packet between any pair of nodes. This delay is formed in the process of passing the packet along each branch of all paths connecting pairs of nodes (the delay also includes the time the packet waits in the queue at the node). In this regard, as an assessment of the criterion for servicing the packet switching subnetwork, it is advisable to consider the average delay in the transmission of the data stream (load of the packet switching subnetwork) along the branch (*ik*). User requirements for quality of service are determined by matrices $P=||p_{ij}||$ and $T=||t_{ij}||$, where t_{ij} is the current value of packet delay between nodes i, j. For a given routing on packet switching subnets for each integral-group path j the total intensity of input flows γ_j is fixed for packet switching mode. For each IGP_j, where $j=1, ..., M$, total intensity of input flows γ_j is assumed to be Poisson, whose message lengths obey an exponential distribution law with mean values $1/\nu_j$.

Let $t_j(\gamma_j, n_j)$ be the packet delay function that depends on the intensity of the packets γ_j, coming to the line j, and the delay in the transmission of these packets mainly depends on the average number of time channels of the *PCM* cycle n_j. Value $\gamma_j \cdot t_j(\gamma_j, n_j)$ is the average packet delay γ_j as they pass through integral group path IGP_j. When describing the model for calculating the optimal generalized channel boundary of a digital network with integrated services, a problem arises related to finding the service efficiency function on the entire integrated network as a whole.

Thus, for the packet switching subnet, the quality of service criterion of this subnet is selected - the average packet delay time in the packet switching subnet.

5. 2. Formulation of the optimization problem of determining the quality on the packet switching subnet

One of the approaches to solving the problem of efficient service on a digital network with integration of services is considered. Namely, in the process of analyzing the design of a digital network with integrated services, an optimization problem is compiled, where the evaluation of the service of the packet switching subnetwork is used as the objective function, and as one of the constraints for this task is the evaluation of the service of the circuit switched subnet. The union of these estimates is provided by their common set of variables $P=\{p_{ij}\}$, $i, j\in V$. The solution of the optimization problem with respect to the set P in each *IGP* for the circuit switched subnet determines the loss probabilities, which in turn minimize the overall delay for the packet switched subnet. As a result, knowing the values of the optimal loss probabilities, it is always possible to determine the most efficient structure of the generalized channel boundary of a digital network with integrated services.

The fact that the total packet delay in the packet switching subnet will directly depend on the set of variables P is convinced by the following reasoning. Changes in the loss probabilities on each branch lead to a change in the value of the transmitted load of the circuit switching subnetwork. Since this skipped load is currently considered serviced, it is compared with the number of time channels serving it. Consequently, any change in the value of the missed load leads to a change in the number of time channels serving this load. And this, in turn, affects the number of time channels provided for the transmission of the flow of the packet switched subnetwork.

The initial data in determining the parameters of the set P on a digital network with integrated services are:

1) the structure of the digital network with the integration of services;

2) circuit-switched and packet-switched input loads, each of which represents the average value of the flow received during the busiest hour;

3) circuit-switched and packet-switched load distribution plans (set of acceptable load transfer paths for both subnets);

4) allowable total load losses of the circuit switching subnetwork;

The integrated services digital network structure includes:

1) the location structure of all nodes of the set V;

2) the topological structure of the set of all branches of E;

3) the number of time channels of the pulse-code modulation cycle;

4) bandwidth and transmission intensity of each pulse-code modulation cycle.

By specifying the input loads of the circuit switching and packet switching subnetworks, let's mean the specification of the matrices $L=||\lambda_{ij}||$ and $\Gamma=||\gamma_{ij}||$ respectively. For each node $i\in V$ the distribution plan for circuit-switched and packet-switched load flows is determined by the respective initial route matrices, which determine the set of valid transmission paths. Further, circuit-switched and packet-switched subnets within an integrated services digital network retain all the requirements that were imposed when describing the model of each of the subnets separately.

The problem of dynamic control of distribution of channels between networks of circuit switching and packet switching in a digital network with integration of services is formulated in the following form. Let some packet delay function $t_j(\gamma_j, n_j)$ be known for each communication line j, depending on the intensity of packets arriving on this line, as well as on the number of channels serving this load. Value $\gamma_j t_j(\gamma_j, n_j)$ represents the average total delay γ_j of packets as they pass through the integral group path IGP_j. Then the average packet delay in the network T, multiplied by the average number of incoming packets per unit time has the form [24]:

$$T\gamma=\sum_{j=1}^{M}\gamma_j t_j\left(\gamma_j,n_j\right), \tag{1}$$

where $\gamma=\sum_{i=1}^{M}\sum_{j=1}^{M}\gamma_{ij}$ is the total sum flow of the packet switching mode.

Let $p_j(\lambda_j, m_j)$ be the function representing the probability that in the circuit switching mode, when the demand flow intensity arrives at the integral group path IGP_j. All m_j channels will be busy serving previous requirements. This function depends on the intensity of the incoming load, the number of time channels served by this load and may be different for each line j. Then the total losses in a digital network with integrated services are:

$$\pi=\sum_{j-1}^{M}\lambda_j p_j\left(\lambda_j,m_j\right), \tag{2}$$

where the loss is measured by the number of circuit-switched requests that fail to establish a connection per unit of time. The problem of optimal distribution of channels in a digital network with integration of services. consists in minimizing with respect to the variable m_j expressions (1) under the following restrictions:

$$\sum_{j-1}^{M}\lambda_j p_j\left(\lambda_j,m_j\right)\le\pi_0, \tag{3}$$

$$N_j=m_j+n_j,\ m_j,n_j\ge 0,\ j=1,2,...,M, \tag{4}$$

$$t_j>0,\ 0<p_j<1,\ j=1,2,...,M, \tag{5}$$

where π_0 is the allowable loss of circuit switched network messages.

Due to the specifics of the organization of the channel in the integrated network, the restriction on the integer number of variables m_j, n_j is not imposed.

It is assumed that temporarily free circuit switched channels can be used to transmit packets, and the possibility of filling speech pauses with packets is not taken into account for simplicity, although this does not change the general algorithm. $\eta_j(\lambda_j, m_j)$ – the average number of free channels of the circuit switching mode in the communication line j, depending on the load λ_j and the number of channels served m_j. Then the objective function takes the following form:

$$T\gamma=\sum_{j=1}^{M}\gamma_j\cdot t_j\left(\gamma_j,N_j-m_j+\eta_j\left(\lambda_j,m_j\right)\right). \tag{6}$$

As a specific objective function, let's consider the average delay in a single-server queuing system [25]:

$$t_j=\frac{1}{\mu_j b_j-\gamma_j}, \tag{7}$$

where b_j is the total throughput allocated to IGP_j for packet switching mode. Since temporarily free circuit-switched channels are also used for packet transmission, then:

$$b_j=c_j\left(n_j+\eta_j\right)=c_j\left(N_j-m_j+\gamma_j\right). \tag{8}$$

The QoS function of a circuit switching network is defined as a function of explicit load losses in an integrated group path IGP_j:

$$\pi_j=\alpha_j p_j\left(\alpha_j,m_j\right), \tag{9}$$

where $\alpha_j=\lambda_j/\gamma_j c_j$ is the average number of messages arriving in the integral group path IGP_j for the average service time of one message, $p_j(\alpha_j, m_j)$ employment probability of m_j channels in IGP_j, which is determined by the Erlang formula:

$$p_j\left(\alpha_j,m_j\right)=\frac{\alpha_j^{v}}{m_j!\sum_{k=0}^{v}\frac{\alpha_j^{k}}{k_j!}}. \tag{10}$$

The average number of busy channels is determined by the formula $\alpha_j(1-p_j)$. Then the average number of time channels that are not occupied by the circuit switched load service used to transmit packets in the packet switched mode will be:

$$\eta_j=m_j-\alpha_j\left(1-p_j\right). \tag{11}$$

Taking into account formulas (7)–(11), the problem of distribution of channel resources has the form:

$$\psi_j\left(x_j-\alpha_j\right)=0,\ \psi_j\ge 0,$$

$$T\gamma=\sum_{j=1}^{M}\frac{\beta_j}{N_j-\alpha_j-\beta_j+\alpha_j p_j}\to\min_{m_j}, \tag{12}$$

$$\sum_{j=1}^{M}\alpha_j p_j\le\pi_0,\ m_j\ge 0,\ j=1,2,\dots M, \tag{13}$$

$$t_j>0,\ 0<p_j<1,\ j=1,2,\ ...,\ M, \tag{14}$$

where $\beta_j=\gamma_j/c_j\mu_j$ is the load intensity on one channel of the integral group path IGP_j in packet switching mode. This problem is solved with respect to the variable m_j, which is contained in the function p_j. For convenience, let's introduce the following notation:

$$x_j=\alpha_j\cdot p_j, \tag{15}$$

$$B_j=\alpha_j+\beta_j-N_j. \tag{16}$$

With these notations, condition (14) can be written as:

$$B_j\le x_j\le\alpha_j,\ j=1,2,\ldots,M. \tag{17}$$

Then problem (12)–(14) will have the following form:

$$T\gamma=\sum_{j=1}^{M}\frac{\beta_j}{x_j-\beta_j}\to\min_{x_j}, \tag{18}$$

$$\sum_{j=1}^{M}x_j\le\pi_0, \tag{19}$$

$$B_j\le x_j\le\alpha_j,\ j=1,2,\ldots,M. \tag{20}$$

Problem (18)–(20) is a convex programming problem with respect to the variable x_j, since the objective function is convex on a convex feasible set of solutions.

Thus, the optimization problem of determining the quality in a packet-switched subnet is obtained.

5. 3. Solving the problem of optimal distribution of channels in a digital network with integration of services by the method of Lagrange

Consider the optimization problem of determining quality in a packet-switched subnet (18)–(20).

To obtain an analytical solution to problem (18)–(20), the method of indefinite Lagrange multipliers is used.

For this problem, the Lagrange function has the form:

$$L=\sum_{j=1}^{M}\frac{\beta_j}{x_j-B_j}+\varphi\left(\sum_{j=1}^{M}x_j-\pi_0\right)+$$
$$+\sum_{j=1}^{M}\psi_j\left(x_j-\alpha_j\right)+\sum_{j=1}^{M}\theta_j\left(B_j-x_j\right), \tag{21}$$

where φ, ψ_j, θ_j are indefinite coefficients. The conditions that the optimal choice x_j must satisfy, taking into account constraints (19), (20), have the form:

$$-\frac{\beta_j}{\left(x_j-\beta_j\right)^2}+\varphi+\psi_j-\theta_j=0, \tag{22}$$

$$\varphi\left(\sum_{j=1}^{M}x_j-\pi_0\right)=0, \tag{23}$$

$$\psi_j\left(x_j-\alpha_j\right)=0,\ \psi_j\ge 0, \tag{24}$$

$$\theta_j\left(B_j-x_j\right)=0,\ \theta_j\ge 0. \tag{25}$$

Since inequality (20) is strict, then in equalities (24) and (25) the indefinite coefficients vanish, i. e.: $\psi_j=0$, $\theta_j=0$, $j=1,\ 2,\ \ldots,\ M$. Then relation (22) implies that $\varphi\neq 0$. Thus, as follows from (23), the stationary point of problem (18)–(20) lies on the boundary of the constraint (19), that is, on the line:

$$\sum_{j=1}^{M}x_j-\pi_0=0. \tag{26}$$

It is easy to obtain a solution to problem (18)–(19), which can be written in the following form:

$$x_j=B_j+\sqrt{\frac{\beta_j}{\varphi}}, \tag{27}$$

$$\frac{1}{\sqrt{\varphi}}=\frac{\pi_0-\sum_{j=1}^{M}B_j}{\sum_{j=1}^{M}\beta_j}. \tag{28}$$

Since $\varphi>0$, then from the last formula let's obtain that $\sum_{j-1}^{M}B_j<\pi_0$. The last expression also follows from condition (20).

Thus, the solution of the optimization problem (18)–(20) is determined by formulas (27), (28). At the same time, by calculating the value x_j using formula (15), it is possible to determine the probability of employment m_j time channels:

$$p_j\left(\alpha_j;m_j\right)=\frac{x_j}{\alpha_j}.$$

Based on the known probability values, using tabulated tables [26], the number of time channels m_j occupied by the service was found.

5. 4. Implementation of the algorithm for calculating the optimal throughput of the integrated digital network

The implementation of the algorithm on a specific numerical example is shown below. Let the Integrated services digital network (ISDN) with six hybrid switching nodes (HSN) be represented as a directed graph in Fig. 1.

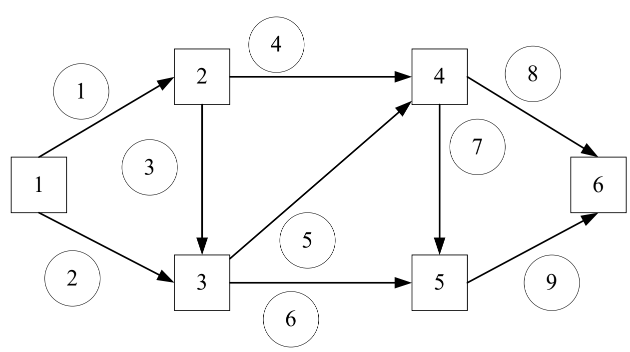

Fig. 1. Integrated digital network with six hybrid switching nodes

Circles indicate Integral Group Path (IGP) numbers. The throughput and number of channels for each path is $C_j=10$ bit/s, $N_j=50$. The service time of one call to the Circuit Switching (CS) network is equal to $1/C_j\nu_j=60$ *s*.

The total allowable losses are $\pi_0=40$ *Erl*.

Calculation data for Circuit Switching (CS) subnet are given in Table 1.

Table 1

Initial input traffic (messages per sec)

F^1	1	2	3	4	5	6
1	–	0.507	0.3	0.1	0.08	0.1
2	–	–	0.6	0.045	0.07	0.06
3	–	–	–	0.567	0.083	0.1
4	–	–	–	–	0.708	0.095
5	–	–	–	–	–	0.642
6	–	–	–	–	–	–

The specified routing for the main directions has the designation:

traffic t_{12}–$1\to2$ (from the first node to the second node);

$t_{13}-1\to3, t_{14}-1\to3\to4, t_{15}-1\to3\to5, t_{16}-1\to2\to4\to6;$

$t_{23}-2\to3,\ t_{24}-2\to4,\ t_{25}-2\to3\to5,\ t_{26}-2\to4\to6;$

$t_{34}-3\to4,\ t_{35}-3\to5,\ t_{36}-3\to5\to6;$

$t_{45}-4\to5,\ t_{46}-4\to6;$

$t_{56}-5\to6.$

Total flows:

$\lambda_1=f_{16}+f_{12}=0.1+0.507=0.607;$

$\lambda_2=f_{15}+f_{14}+f_{13}=0.49;$

$\lambda_3=f_{25}+f_{23}=0.67;$

$\lambda_4=f_{16}+f_{24}+f_{26}=0.205;$

$\lambda_5=f_{14}+f_{34}=0.667;$

$\lambda_6=f_{15}+f_{25}+f_{36}+f_{35}=0.333;$

$\lambda_7=f_{45}=0.708;$

$\lambda_8=f_{16}+f_{46}+f_{26}=0.255;$

$\lambda_9=f_{36}+f_{56}=0.742.$

Calculation data for Packet Switching (PS) subnet are given in Table 2.

Table 2

Initial input traffic (messages per sec)

F^2	1	2	3	4	5	6	Sum
1	–	0.2	0.7	1.3	0.5	4.7	4.7
2	–	–	1.2	1.0	0.8	0.06	4.5
3	–	–	–	0.567	0.083	0.1	2.1
4	–	–	–	–	0.708	0.095	3.4
5	–	–	–	–	–	0.642	0.3
6	–	–	–	–	–	–	γ=15.0

The specified routing of the main directions.

$t_{12}-1\to2;$

$t_{13}-1\to3, t_{14}-1\to2\to4, t_{15}-1\to3\to5, t_{16}-1\to3\to5\to6;$

$t_{23}-2\to3,\ t_{24}-2\to4,\ t_{25}-2\to3\to5,\ t_{26}-2\to4\to6;$

$t_{34}-3\to4,\ t_{35}-3\to5,\ t_{36}-3\to4\to6;$

$t_{45}-4\to5,\ t_{46}-4\to6;$

$t_{56}-5\to6.$

Total flows:

$\gamma_1=f_{14}+f_{12}=2.2;$

$\gamma_2=f_{15}+f_{16}+f_{13}=2.5;$

$\gamma_3=f_{23}+f_{25}=2.0;$

$\gamma_4=f_{14}+f_{24}+f_{26}=4.5;$

$\gamma_5=f_{25}+f_{34}=0.667;$

$\gamma_6=f_{15}+f_{25}+f_{16}+f_{35}=0.333;$

$\gamma_7=f_{45}=1.8;$

$\gamma_8=f_{16}+f_{46}+f_{26}=4.2;$

$\gamma_9=f_{16}+f_{56}=0.8$

The average length of transmitted packets between nodes (bits) is shown in Table 3.

Table 3

Average length of transmitted packets between nodes (bits)

Node number	1	2	3	4	5	6
1	–	100	100	80	80	120
2	–	–	80	100	120	100
3	–	–	–	120	100	80
4	–	–	–	–	80	80
5	–	–	–	–	–	120
6	–	–	–	–	–	–

Average packet length in IGP (bits):

$1/\mu_1=(0.2\times100+2\times80):(0.2+2.0)=82;$

$1/\mu_2=94;$

$1/\mu_3=96;$

$1/\mu_4=91;$

$1/\mu_5=91;$

$1/\mu_6=100;$

$1/\mu_7=87$;

$1/\mu_8=80$;

$1/\mu_9=120$.

Numerical characteristics calculation of the optimal ISDN throughput are given in Table 4.

Table 4

Calculation of the optimal throughput of the ISDN

α_j	β_j	B_j	x_j	p_j	m_j	$x_j–B_j$	T_j	R_l	D_l	A_l	m_l
36.4	18.04	4.41	4.6535	0.1278	36	0.2135	84.4772	38.94	5.4	41.25	42
28.8	23.5	2.3	2.5333	0.0888	31.5	0.2437	96.4173	–	–	–	–
40.2	19.3	8.4	9.4203	0.2343	33.5	0.0203	945.4635	43.97	4.34	48.32	44
13.3	40.35	3.25	3.5717	0.2904	10.3	0.0817	127.2765	–	–	–	–
40.0	13.65	3.66	3.8336	0.959	42	0.1858	73.4831	42.28	3.44	46.21	43
20.0	32.0	2	2.2844	0.1142	22	0.2844	112.5113	–	–	–	–
42.5	14.4	6.9	7.0808	0.1668	39	0.1908	75.4759	44.64	3.95	47.38	45
15.3	36.54	1.84	2.1439	.01401	16	0.3039	120.228	–	–	–	–
44.5	9.6	4.1	4.2557	0.0956	46	0.1558	61.625	–	–	–	–

The numerical results given in the table were obtained by implementing a mathematical model of the optimal distribution of the channel resources of bandwidth of ISDN in the algorithmic C++ language for this example with six hybrid switching nodes, presented in the form of a directed graph in Fig. 1.

6. Discussion of results of the study of the optimal distribution of bandwidth channel resources of the integrated digital network

In this paper, a general description of the problem of calculating the optimal values of the generalized channel boundary between the circuit switching and packet switching subnets within the ISDN was presented. The initial data of a digital network with integrated services are described: topological structure, channel resources of the network, throughput of each channel, etc.

Depending on the information parameters (load state) and the situation on the integrated network, the ISDN control system will move the threshold in one direction or another, redistributing the bandwidth of the pulse code modulation cycle between messages transmitted in circuit switching or packet switching modes, i. e. in fact, the process of redistribution of the mixed path is underway. The threshold of the pulse-code modulation cycle on each communication channel forms a channel boundary, and the set of all channel boundaries is considered as a generalized boundary, which conditionally leads to the division of the ISDN into two subnets: the circuit switching subnetwork and the packet switching subnetwork [27]. If the generalized boundary is permanently fixed, then the two circuit-switched and packet-switched subnets operate independently of each other, and the free time channels of one subnet are not used to transmit data to the other subnet. With a moving generalized border, the bandwidth is used more efficiently [28], since in this case the ISDN has the opportunity to dynamically redistribute them depending on the load conditions of the circuit switching and packet switching subnets. Thus, the redistribution of channel resources to the ISDN makes it possible to obtain optimal characteristics and parameters of the quality of service of the integral network.

In this paper, a pulse-code modulation cycle is transmitted as a block of information along the network path, the time positions of which can be used to transmit information both in the circuit switching mode and in the packet switching mode. In this case, the pulse-code modulation cycle is conditionally divided by a dynamically shifted threshold into two parts, one of which is occupied by the transmission of information in the circuit switching mode, and the other in the packet switching mode. Depending on the information parameters and the state of the communication network, the communication network management system will move the threshold in one direction or another, redistributing the bandwidth of the pulse-code modulation cycle between messages transmitted in the circuit switching and packet switching modes.

For each integrated group path (IGP), fixed-length pulse-code modulation cycles are transmitted, in which information transmission over time $\tilde{N}$ channels can be organized. Moreover, each of the $\tilde{N}$ channels can be used both for circuit switching modes and for packet switching modes.

During the work, the circuit switching subnet was investigated without taking into account the transmission of an excess flow of multichannel calls in bypass directions. At the same time, for the circuit switching subnetwork, the initial data of the problem of calculating probabilistic characteristics are specified, the characteristics that are determined in the process of solving the problem are listed, restrictions (3)–(5) are given, and some assumptions are described that allow the study of such a model to be adequately approximated to the functioning of a real network. The classical Erlang formula is studied (10) for a queuing system with denials of service for multichannel calls.

Furthermore, the packet switching subnet within the ISDN was examined. At the beginning, the basic concepts of the packet switching subnetwork are presented, namely, the issues of routing data packets and methods of their transportation over communication channels, data packet formats, methods of addressing information packets, methods of message transmission and flow control on packet switching networks were considered. Then, the timing characteristics of the packet switched subnetwork (8), (9) are described.

The communication channel of the subnet is investigated as a single-instrument model of the queuing system (7). This system is characterized by the average time of packet delivery to the destination node. Mutual influence of quality of service parameters between circuit switching and packet switching subnets (8), (9), (11) is established. A feature of this model is the study of the throughput of the packet switching subnetwork, taking into account the throughput of the circuit switching mode.

For the packet switching subnetwork, the quality of service criterion for this subnetwork is chosen-the average packet delay time in the packet switching subnetwork.

By means of mathematical transformations, the dependence of the total delay function on the value of the missed flow of the circuit switching subnetwork is obtained.

The problem of dynamic control of distribution of channels between networks of circuit switching and packet switching in ISDN is formulated in the form (1) when conditions (3)–(5) are met. Due to the specific organization of the channel in an integrated network, there is no restriction on the integer nature of variables representing the number of serviced channels and the integer nature of the average number of time slots. As a specific objective function, let's consider the average delay in a single-instrument queuing system (7). The quality of service function of the circuit switching network is defined as a function of explicit load losses in the IGP_j (9). The probability of occupancy of channels in IGP_j was determined by the Erlang formula (10). Further, after some mathematical transformations, the problem of optimal distribution of the ISDN bandwidth without taking into account bypass directions in mathematical form (18)–(20) is given, which is solved by the method of indefinite Lagrange multipliers, where the Lagrange function has the form (21). The solution of the optimization problem (18)–(20) is determined by formulas (26), (27).

For the numerical implementation of the obtained mathematical model, an ISDN with six hybrid switching nodes is considered. It is presented in the form of a directed graph in Fig. 1. The calculation data for circuit switching and packet switching subnets, and the average length of transmitted packets between nodes are shown in Tables 1–3.

The calculation of the optimal throughput of the ISDN is represented in Table 4.

When describing the model for calculating the optimal generalized ISDN channel boundary, a problem, related to finding the service efficiency function on the entire integrated network as a whole, arises. This problem is solved by composing an optimization problem in which the evaluation of the maintenance of a packet-switched subnet is used as an objective function, and the evaluation of the maintenance of a circuit-switched subnet is used as one of the limitations of the task.

The obtained results of the study can be applied to ISDN based on pulse code modulation systems with time division multiplexing, in which the hybrid switching method is implemented.

The question of stability of the solution disappears, since the results are obtained by rigorous mathematical calculations.

The disadvantage of the work is that the flow of calls in the mathematical model is taken as the simplest or primitive. Real call flows, for example, with a large amount of losses, have a more complex structure, and the solution of problems is carried out by the method of statistical modeling.

The research can be continued in the direction of generalizing the approach considered in this article to other types of networks, not only to ISDN, applying similar methods to other technologies, such as modern IP networks, next-generation networks, etc.

7. Conclusions

1. A digital network with integrated services is considered, based on pulse-code modulation systems with time division multiplexing, in which the hybrid switching method is implemented, consisting of hybrid switching nodes and integral group paths connecting them. The ISDN includes territorially remote hybrid switching nodes connected by integral group paths. At the same time, depending on the transmission method, heterogeneous information is divided into two main methods: the channel switching method and the packet switching method. As a block of information, a pulse-code modulation cycle is transmitted along the network path, which, at the same time, is conventionally divided by a dynamically shifted threshold into two parts, one of which is busy transmitting information in the channel switching mode, and the other in the packet switching mode. To calculate the basic characteristics of the packet switching subnetwork within the ISDN, this subnetwork is considered as a system of maintenance with expectation. The distribution of flows on the network is determined by the deterministic routing selection procedures used to transfer information in the packet switching mode. As for the packet switching subnet, it is considered that for each node of the packet switching subnet a load distribution plan is specified. Since the packet switching subnet within the ISDN is considered as a system with unlimited expectation, the quality of service on it is estimated by the time delay in the transmission of a packet between any pair of nodes. This delay is formed in the process of passing the packet along each branch of all paths connecting pairs of nodes (the delay also includes the time the packet waits in the queue at the node). In this regard, it is advisable to consider the average delay in the transmission of a data stream as an assessment of the service criterion for the packet switching subnetwork.

2. In the process of analyzing the design of the ISDN, an optimization problem is composed, where an assessment of the maintenance of the packet switching subnet is used as an objective function, and an assessment of the maintenance of the channel switching subnet is used as one of the limitations for this task. The solution of the optimization problem with respect to P (the set of probabilities of load losses of input call flows along the paths) in each integral group path for the channel switching subnet determines the probabilities of losses, which in turn minimizes the overall delay for the packet switching subnet.

3. A feature of the model that establishes the interdependence of the quality of service indicators of the channel switching and packet switching subnets is the study of the bandwidth of the packet switching subnet taking into account the bandwidth of the channel switching mode, while the subnet communication channel is considered as a single-device model of the queuing system. This system is characterized by the average time of package delivery to the destination node. Under these conditions, the task of dynamic control of channel distribution between channel switching and packet switching networks in the ISDN is set. The quality function of the channel switching network maintenance is defined as a function of the apparent load losses in IGT_j, and the probability of channel occupancy in IGT_j is determined by the Erlang formula. After that, let's obtain a mathematical formulation of the problem of optimal distribution of the ISDN bandwidth without taking into account the bypass directions. To solve this problem, various methods can be used, such as linear programming, dynamic programming and other algorithms. In this paper, let's use the method of indefinite Lagrange multipliers, as it is simple and convenient to implement on modern computers.

4. The task of calculating bandwidth for circuit and packet switched subnets in an integrated ISDN network is directly related to the quality of service function in this

network. The quality of service function determines the level of satisfaction of the needs of network users and includes various parameters that reflect the efficiency, reliability and performance of the network. In the context of this task, quality of service parameters such as latency, packet loss and bandwidth become important criteria when calculating bandwidth for circuit-switched and packet-switched subnets.

In the process of solving this problem, the following parameters of the service quality function were determined:

1) the general flow of packet switching mode;

2) permissible loss of messages in a circuit-switched network;

3) total loss of messages in the integrated ISDN network;

4) temporarily free circuit-switched channels used for packet transmission;

5) QoS (quality of service) function of a circuit-switched network;

6) the average number of temporary channels not occupied by the load in the circuit-switched mode;

7) the intensity of the load on the IGPj channel in packet-switched mode.

Calculations and analysis of these parameters determine the optimal bandwidth for circuit-switched and packet-switched subnets in an integrated ISDN network, ensuring optimal quality of service.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorial or otherwise, which could affect the research and its results presented in this article.

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