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## ENHANCEMENT OF THE ADAPTIVE ROUTING TENSOR MODEL IN THE INFOCOMMUNICATION NETWORK WITH PROVIDING QUALITY OF EXPERIENCE BY THE R-FACTOR

Об'єктом дослідження є процеси маршрутизації та забезпечення якості сприйняття послуг, що надаються кінцевим користувачам, в інфокомунікаційній мережі. Для проведення дослідження в роботі запропоновано вдосконалення тензорної моделі адаптивної маршрутизації в інфокомунікаційній мережі із забезпеченням сприймаємої якості обслуговування за  $R$ -фактором. За основу було взято потокову модель маршрутизації, яка враховувала ймовірні втрати пакетів, викликані перевантаженням елементів мережі, та була представлена умовами реалізації багатошляхової стратегії маршрутизації, збереження потоку та запобігання перевантаження каналів зв'язку. Для отримання в аналітичному вигляді умов забезпечення якості сприйняття за показником  $R$ -фактору здійснено тензорний опис інфокомунікаційної мережі. Це дозволило отримати аналітичні вирази для розрахунку середньої міжкінцевої затримки та ймовірності втрат пакетів, які були використані для формування  $QoE$ -умов за показником  $R$ -фактору.

В рамках запропонованої моделі рішення технологічної задачі адаптивної маршрутизації було зведено до розв'язання оптимізаційної задачі нелінійного програмування з розрахунку маршрутних змінних. Введений критерій оптимальності дозволив забезпечити адаптивний характер маршрутних рішень, коли підвищення  $QoE$ -вимог призводило до зростання об'ємів використаного мережного ресурсу. Для розв'язання поставленої задачі використовувались методи математичного програмування, які реалізовані в пакеті *MatLab*.

Проведене дослідження на фрагменті інфокомунікаційної мережі дозволило оцінити адекватність і ефективність запропонованого підходу. За допомогою отриманих результатів досліджень вдалося забезпечити виконання заданих  $QoE$ -вимог за показником  $R$ -фактору до послуг, що надаються кінцевим користувачам. При цьому, використання запропонованої моделі характеризується більшою ефективністю щодо балансування навантаження за множиною маршрутів в інфокомунікаційній мережі. Про це свідчило те, що при заданому значенні  $R$ -фактору, з ростом інтенсивності трафіку, що надходить до інфокомунікаційної мережі, здійснювалось поступове збільшення кількості задіяних маршрутів. Тобто мережний ресурс розподілявся поступово та ефективніше на 7–10 % відносно відомих аналогів, які під час вирішення цієї ж задачі одразу використовують всі доступні маршрути.

**Ключові слова:** інфокомунікаційна мережа, якість сприйняття,  $R$ -фактор, адаптивна маршрутизація, тензорна модель.

Received date: 25.01.2020

Accepted date: 11.03.2020

Published date: 30.06.2020

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### 1. Introduction

Today, Quality of Service (QoS) in infocommunication networks (ICN) is a key goal in solving problems associated with their design and operation. This is confirmed by the current trend towards convergence of networks of various types, the rapid growth of diverse traffic in networks, with the advent of multimedia applications and services that work in real time, etc. At the same time, control of the Quality of Experience (QoE) at the user level comes first, which is especially important when providing multimedia services.

Considering and analyzing traffic management as the main tool to achieve a given QoS, it should be noted that the highest efficiency of ICN operation is achieved when implementing adaptive routing. This fact is due to the use of resources (nodes, links and paths) of the network in ac-

cordance with QoS requirements, as well as the amount of available link and buffer resources. Focusing precisely on such an approach, the following urgent scientific and technical problem arises: to develop an adaptive routing model in the infocommunication network with ensuring QoE level.

The solution to the formulated problem involves ensuring end-to-end quality of service, which will combine the network performance (NP), the quality of service and the quality of experience to the end user.

### 2. The object of research and its technological audit

The object of research is the routing and quality of experience (QoE) processes in the infocommunication network. Moreover, the provision of QoE in the future is

understood as the provision of set values of such an important indicator as the R-factor, which is used in assessing the quality of the provision of VoIP services.

Today, providing a given level of QoE in the information network is a rather complicated theoretical and technological task. This is due to the fact that in accordance with the methodology for assessing the R-factor [1–3], its value is influenced by many factors, ranging from the parameters of the physical link to the characteristics of the end terminal, for example, a mobile phone or smartphone.

To solve the problem of ensuring the QoE level, especially in conditions of a limited network resource, one of the effective approaches is the optimization of adaptive routing processes.

### 3. The aim and objectives of research

*The aim of the proposed research* is to provide a given level of QoE in terms of R-factor using adaptive routing with control of the average end-to-end delay and the probability of packet loss in the network.

To achieve this aim it is necessary to solve the following objectives:

1. To choose the appropriate flow-based model of adaptive routing, taking into account the probable packet loss, which is important in conditions of network congestion.
2. To obtain in analytical form the conditions for providing QoE by the R-factor indicator based on the implementation of adaptive routing with control of end-to-end delay and the probability of packet loss.
3. To formulate in an optimization form and solve the problem of adaptive routing in ICN with justification of the form and type of the optimality criterion and the set of constraint-conditions.
4. To conduct an experimental study of the proposed flow-based model to assess its adequacy and effectiveness.

### 4. Research of existing solutions to the problem

Analyzing existing studies in the field of ensuring and assessing the level of QoE, several approaches based on subjective and objective methods should be noted [4, 5].

So, the use of subjective methods, which are described in [6, 7], allows to evaluate the QoE level mainly only at the moment when the audio and video information is subjected to distortions that occur during digitization, compression, transmission, decoding, etc. For example, for a video stream, these methods are based on subjective metrics such as Single-Stimulus Continuous Quality Evaluation (SSCQE), Double Stimulus Impairment Scale (DSIS) and Double Stimulus Continuous Quality Scale (DSCQS) [8, 9]. And for the subjective assessment of the audio stream, Perceptual Speech Quality Measurement (PSQM) mechanisms are usually used [10, 11]. The disadvantage of these methods is, firstly, the complexity of the quality assessment process itself, because they are based on statistical algorithms, and, secondly, this process is characterized by high time costs.

Subjective methods also include the well-known Mean Opinion Score (MOS) method described in [12]. However, this method does not allow real-time monitoring of QoE level and timely response to quality degradation.

A common drawback of subjective methods is that they:

- require the consumption of additional network resources, which are already limited;
- do not allow quantifying the network performance factors that affect the QoE level, namely the average delay and packet loss;
- require specific network equipment settings to evaluate QoE.

Unlike subjective methods, objective methods are more informative and allow to assess the level of QoE based on the analysis of the structural and functional characteristics of the network. So, the highest results among existing studies were achieved using the objective method, which is based on the E-model presented in [13, 14]. The result of calculating the QoE level using the E-model is an indicator – the R-factor, which allows to assess the level of the quality of experience provided to users on the network. This QoE indicator combines not only individual characteristics of signals, but also network indicators of transmission quality: average delay and probability of packet loss. However, despite all these advantages, the main drawback of this method is the lack of a direct relationship between the R-factor and network performance [15]. Therefore, a promising scientific problem arises in obtaining this dependence in order to further assess the level of QoE in terms of the R-factor.

The solution to this problem requires the revision of mathematical models and methods, which are the basis of modern protocol solutions, in the direction of using the tensor approach [16, 17]. According to the analysis, similar mathematical solutions already exist that are proposed and presented in [18, 19]. And although the use of tensor models complicates both the mathematical description of the problem and its solution, such difficulties are compensated (in comparison with the known analogues) by the effectiveness of route decisions in relation to the level of quality of service. A characteristic feature of the tensor QoE routing models described in [20, 21] is the non-adaptive nature of the solutions, when during routing, load balancing is carried out along the whole set of available routes. This significantly narrows the scope of such solutions, limiting it to ICN overload. Therefore, there is a need to improve the well-known tensor models of QoE routing by providing an adaptive route solution.

### 5. Research methods

The graph theory was used as a research method, due to which the network structure was described. To obtain in an analytical form the conditions for ensuring QoE in terms of the R-factor, the tensor research methodology and queuing theory are used. To solve the formulated optimization problem of nonlinear programming used mathematical programming methods that are implemented in the MatLab package.

### 6. Research results

#### 6.1. Definition and description of the basic tensor routing model with ensuring quality of service according to the R-factor.

The first step in the research process is the choice of a basic mathematical routing model. So, according to the analysis [16, 18, 19], the existing routing models are divided into graph and flow-based models. Usually, the use

of graph models is aimed at minimizing the conditional length of the calculated path, which as a whole only contributes to the indirect improvement of QoS indicators, but without ensuring their specified or maximum permissible values. When using flow-based routing models, a more detailed account of both the characteristics of packet flows and ICN parameters, for example, bandwidth of communication links, is provided, which improves the efficiency of load balancing in terms of QoE. One of the relatively new directions in the mathematical modelling of routing processes is the use of the tensor approach, which has established itself as an effective means of a holistic and multi-faceted description of ICN [20, 21]. Therefore, in this work, let's choose a flow-based routing model with its subsequent tensor generalization to obtain conditions for ensuring QoE in terms of the R-factor with control of the end-to-end delay and packet loss probability.

Let the structure of the infocommunication network be described using a one-dimensional network:

$$S = (U, V),$$

where  $U = \{u_i, i = \overline{1, m}\}$  is the set of zero-dimensional simplexes – network nodes (routers),  $m$  – the total number of nodes in the network  $S$ . Set of one-dimensional simplexes are edges of a network  $V = \{v_z = (i, j); z = \overline{1, n}; i, j = \overline{1, m}; i \neq j\}$  simulates communication links where a edges  $v_z = (i, j)$  modelling  $z$ -th link, which connects  $i$ -th and  $j$ -th routers of the ICN through the appropriate  $j$ -th interface, and  $n$  is the total number of edges in the network  $S$ . For each link simulated by a edges (arc)  $v_z = (i, j) \in V$ , its bandwidth is set, which will be denoted by  $\varphi_z$ , and through  $\varphi_{i,j}$ , and will be measured in packets per second (1/s). Each network router has several interfaces through which it transmits packets to its neighbouring nodes. Moreover, the interface numbers for each individual node correspond to the numbers of neighbouring nodes that are connected through them. Then  $\varphi_{i,j}$  actually determines the bandwidth of the  $j$ -th interface of the  $i$ -th node.

To implement adaptive routing, it is necessary to ensure the calculation of route variables  $x_{i,j}^k$ , which characterize the portion of intensity of the  $k$ -th flow in the link  $(i, j)$ . The following conditions are imposed on route variables:

$$0 \leq x_{i,j}^k \leq 1. \tag{1}$$

The conditions of the flow conservation on network routers, taking into account possible packet losses caused by congestion of the queue buffer, take the form [19, 20]:

$$\begin{cases} \sum_{j(i,j) \in V} x_{i,j}^k = 1, \text{ if } k \in K, i = s_k; \\ \sum_{j(i,j) \in V} x_{i,j}^k - \sum_{j(j,i) \in V} x_{j,i}^k (1 - p_{j,i}^k) = 0, \text{ if } k \in K, i \neq s_k, d_k; \\ \sum_{j(j,i) \in V} x_{j,i}^k (1 - p_{j,i}^k) = b^k, \text{ if } k \in K, i = d_k, \end{cases} \tag{2}$$

where  $K$  is the set of flows in the network;  $s_k$  is the sender router;  $d_k$  is the destination router of the packets of  $k$ -th flow;  $b^k$  is the portion of the  $k$ -th stream served by the network, i. e. packets which are successfully delivered to the receiving router;  $p_{i,j}^k$  is the probability of packet loss of the  $k$ -th flow on the  $j$ -th interface of the  $i$ -th router.

If, for example, the operation of the  $j$ -th interface of the  $i$ -th router is modelled by a  $M/M/1/N$  queuing system with failures of the form, then the probability of packet loss of the  $k$ -th flow can be calculated as follows:

$$p_{i,j}^k = \frac{(1 - \rho_{i,j})(\rho_{i,j})^N}{1 - (\rho_{i,j})^{N+1}}, \tag{3}$$

where  $\rho_{i,j} = \frac{\sum_{k \in K} \lambda_k^{(req)} x_{i,j}^k}{\varphi_{i,j}}$  is the utilization coefficient of

the  $j$ -th interface on the  $i$ -th node;  $N = \Theta_{buf} + 1$  is the maximum number of packets that can be on the interface, including buffer ( $\Theta_{buf}$ ) and the link itself;  $\lambda_k^{(req)}$  is the average intensity of the  $k$ -th packet flow (1/s) at the input to the ICN, the value of which directly determines the bandwidth requirements required for this flow.

To ensure control over the process of overloading links and queues, the following restrictions are introduced into the model structure [20]:

$$\sum_{k \in K} \lambda_k^{(req)} x_{i,j}^k < \varphi_{i,j} \text{ at } (i, j) \in V. \tag{4}$$

Then, to take into account the possible loss of packets, the intensity of the aggregate flow in the link  $(i, j)$  is calculated as:

$$\lambda_{i,j} = \sum_{k \in K} \lambda_k^{(req)} x_{i,j}^k (1 - p_{i,j}^k). \tag{5}$$

The intensity of the  $k$ -th flow of packets that are dropped (lost) on the  $j$ -th interface of the  $i$ -th router can be calculated using the following formula:

$$r_{i,j}^k = \lambda_k^{(req)} x_{i,j}^k p_{i,j}^k. \tag{6}$$

Accordingly, the intensity of successfully transmitted (i. e. lossless) packets of the  $k$ -th flow in the communication link, which is simulated by the edges  $(i, j)$ , is determined as follows:

$$\lambda_{i,j}^k = \lambda_k^{(req)} x_{i,j}^k (1 - p_{i,j}^k). \tag{7}$$

In general, the QoE requirements for speech transmission for a given type of terminal equipment and the codec used in accordance with the recommendations of ITU-T [13, 14] can be written as follows:

$$R \geq R_{(req)} \text{ at } R = R_0 - I_{dd}(T_a) - I_{e-eff}(P_{pl}), \tag{8}$$

where  $I_{dd}(T_a)$  is the coefficient of quality degradation due to long delay, as a function of network delay,  $I_{e-eff}(P_{pl})$  is the quality reduction factor, caused by loss of audio packets, which are determined by such expressions:

$$I_{dd}(T_a) = \begin{cases} 0, T_a \leq 100 \text{ ms}; \\ 25 \left[ (1 + X^6)^{\frac{1}{6}} - 3 \left( 1 + \left[ \frac{X^6}{3} \right]^{\frac{1}{6}} \right) \right] + 2, T_a > 100 \text{ ms}; \end{cases} \tag{9}$$

$$I_{e-eff}(P_{pl}) = I_e + (95 - I_e) \frac{P_{pl}}{\frac{P_{pl}}{BurstR} + B_{pl}}, \tag{10}$$

where  $X = \log \left( \frac{T_a}{100} \right) / \log 2$ ;  $I_e$  is the coefficient of quality degradation due to the use of low-speed codecs;  $T_a$  is the average end-to-end packet delay in the network;  $P_{pl}$  is the total probability of packet loss in the network;  $B_{pl}$  is the factor taking into account the stability of the codec to losses;  $BurstR$  is the coefficient of «burst» of losses.

In the course of ensuring the fulfilment of conditions (8), taking into account (9) and (10), it is important to have mathematical expressions that analytically describe the relationship of route variables (1), traffic characteristics, network parameters, end-to-end delay  $T_a$ , and the probability of packet loss  $P_{pl}$ . Based on the results obtained in [18–20], it is advisable to apply an improved tensor approach to modelling routing processes in infocommunication networks.

**6.2. Formalization of conditions for ensuring quality of service using a tensor model of the network.** According to tensor formalization [22–24], the poles of the network are the nodes that model the routers, through which one or another packet flow enters or leaves the ICN. The following structural characteristics of the network  $S$  will also be used for research:  $\kappa(S)$  is the number of basic interpol paths in the network  $S$ ;  $\vartheta(S)$  is the number of basic internal node pairs in the network  $S$ , where the set of internal node pairs includes all node pairs except the pole.

In the case of ICN simulation with a connected one-dimensional network  $S$ , the structural characteristics are related by the following dependencies:

$$\kappa(S) = n - m + 2; \quad \vartheta(S) = m - 2. \quad (11)$$

On the structure of the infocommunication network, a discrete  $n$ -dimensional geometric space is introduced, that is, its size is determined by the number of communication links in ICN.

Depending on the aspect of consideration, ICN in the introduced discrete  $n$ -dimensional space can be determined by a number of coordinate systems (CS) in which different types of basic paths act as coordinate axes [22–24]: edges, contours, node pairs, sections, and the like.

In the framework of this work in the introduced discrete  $n$ -dimensional space orthogonal coordinate systems will be taken into account, in which the following projections of tensors of the main functional parameters of ICN are considered:  $\{v_z, z = \overline{1, n}\}$  is the coordinate system of network edges, projections of tensors in which will be denoted by index  $v$ ;  $\{\gamma_i, i = \overline{1, \kappa}\}$  is the coordinate system of interpol paths and internal node pairs  $\{\varepsilon_j, j = \overline{1, \vartheta}\}$  of the network  $S$ , the projections of the tensor in which will be denoted by the index  $\gamma\varepsilon$ . The orthogonality of these coordinate systems is justified by the fact that in accordance with expressions (11) the condition is fulfilled:

$$n = \kappa(S) + \vartheta(S).$$

In the entered  $n$ -dimensional space, the infocommunication network for each individually selected packet stream, for which it is necessary to obtain conditions for quality of service, can be described using a mixed divalent tensor [21–23]:

$$Q = T \otimes \Lambda, \quad (12)$$

where  $\otimes$  is the tensor multiplication operator;  $T$  is the univalent covariant tensor of average packet delays;  $\Lambda$  is the univalent contravariant tensor of average flow intensities in the coordinate paths of the network. In the general case, the components of the mixed divalent tensor  $Q$  (12) are interconnected by means of the corresponding metric tensors [22–24]:

$$T = E\Lambda \quad \text{and} \quad \Lambda = GT, \quad (13)$$

where  $E$  is the double covariant metric tensor;  $G$  is the double the contravariant metric tensor.

In index form, expressions (13) take the following form:

$$\tau_j = e_{ji} \lambda^i \quad \text{and} \quad \lambda^i = g^{ij} \tau_j, \quad (i, j = \overline{1, n}), \quad (14)$$

where  $\tau_j$  is the average packet delay along the  $j$ -th coordinate path (s);  $\lambda^i$  is the the average intensity of the flow of packets transmitted along the  $i$ -th coordinate path (1/s). Tensor equations (13) coordinates the network of edges will take the following form:

$$T_v = E_v \Lambda_v \quad \text{and} \quad \Lambda_v = G_v T_v, \quad (15)$$

where  $\Lambda_v$  and  $T_v$  are projections of tensors  $\Lambda$  and  $T$  in CS of the edges, respectively, which are represented by  $n$ -dimensional vectors of flow intensity and average packet delay in ICN links;  $E_v = \|e_{ij}^v\|$  is the projection of the double covariant metric tensor  $E$  in the CS of edges, which is represented by the diagonal  $n \times n$ -matrix;  $G_v = \|g_{ij}^v\|$  is the projection of the double contravariant metric tensor  $G$ , which is also represented by the corresponding diagonal  $n \times n$ -matrix. In this case, the following rule holds:

$$E_v = [G_v]^{-1}, \quad (16)$$

where  $[\cdot]^{-1}$  is the matrix transpose operation.

Similarly, in the coordinate system of the interpol paths and internal node pairs of the network, tensor equations (13) will have the following form:

$$T_{\gamma\varepsilon} = E_{\gamma\varepsilon} \Lambda_{\gamma\varepsilon} \quad \text{and} \quad \Lambda_{\gamma\varepsilon} = G_{\gamma\varepsilon} T_{\gamma\varepsilon}, \quad (17)$$

where  $\Lambda_{\gamma\varepsilon}$  and  $T_{\gamma\varepsilon}$  are projections of tensors and in the CS of interpol paths and internal node pairs, which are represented by  $n$ -dimensional vectors of flow intensity and average packet delay in the corresponding interpol paths and internal node pairs of ICN;  $E_{\gamma\varepsilon} = \|e_{ij}^{\gamma\varepsilon}\|$  is the projection of a double covariant metric tensor  $E$  in the CS of interpol paths and internal nodal pairs, which is represented by a diagonal  $n \times n$ -matrix;  $G_{\gamma\varepsilon} = \|g_{ij}^{\gamma\varepsilon}\|$  is the projection of a double contravariant metric tensor  $G$  in the CS of interpol paths and internal node pairs, which is also represented by the corresponding diagonal  $n \times n$ -matrix.

By analogy with (16), the rule is valid:

$$E_{\gamma\varepsilon} = [G_{\gamma\varepsilon}]^{-1}. \quad (18)$$

The law of contravariant coordinate transformation when changing the considered CSs can be described by a non-singular  $n \times n$ -matrix  $C_{\gamma\varepsilon}^v$  [23–25]:

$$\Lambda_v = C_{\gamma\varepsilon}^v \Lambda_{\gamma\varepsilon}, \tag{19}$$

where  $n$ -dimensional vector  $\Lambda_{\gamma\varepsilon}$ , which is a projection of the tensor  $\Lambda$  in the CS of the interpolator paths and internal node pairs, has the following structure:

$$\Lambda_{\gamma\varepsilon} = \begin{bmatrix} \Lambda_\gamma \\ \Lambda_\varepsilon \end{bmatrix}; \quad \Lambda_\gamma = \begin{bmatrix} \lambda_\gamma^1 \\ \vdots \\ \lambda_\gamma^j \\ \vdots \\ \lambda_\gamma^\kappa \end{bmatrix}; \quad \Lambda_\varepsilon = \begin{bmatrix} \lambda_\varepsilon^1 \\ \vdots \\ \lambda_\varepsilon^p \\ \vdots \\ \lambda_\varepsilon^\vartheta \end{bmatrix}, \tag{20}$$

where  $\Lambda_\gamma$  is the  $\kappa$ -dimensional vector of flow intensities along the basic interpolator paths of the network;  $\Lambda_\varepsilon$  is the  $\vartheta$ -dimensional vector of flow intensities between the nodes that form the basic internal node pairs;  $\lambda_\gamma^j$  and  $\lambda_\varepsilon^p(t)$  are intensity of the flow along the  $j$ -th basic interpolator path ( $\gamma_j$ ) and the flow entering and leaving the network through the nodes, which create the  $p$ -th basic internal node pair ( $\varepsilon_p$ ), respectively.

The projection coordinates of a double contravariant metric tensor  $G$  in the coordinate system of network edges can be represented by the values of the diagonal elements of the matrix  $G_v$  [17–19]:

$$g_{ii} = \frac{\lambda_i (1 - \rho_i^{N+1})(1 - \rho_i) \lambda_v^i}{\rho_i - \rho_i^{N+2} - (N+1)\rho_i^{N+1}(1 - \rho_i)}, \tag{21}$$

where  $\rho_i$  is the utilization coefficient of the  $i$ -th link, which is calculated according to expression (3), namely  $\rho_i = \lambda_i / \varphi_i$ ;  $\lambda_i$  is the total intensity of all packet flows sent to  $i$ -th link;  $\lambda_v^i$  is the intensity of the packet flow, which is considered in terms of building a tensor model, in the  $i$ -th communication link of the ICN.

Further research will be based on the fact that the average end-to-end delay of packets transmitted between a given pair of routers (network poles) using a set of routes  $P$ , is calculated by the following formula:

$$\tau_{MP} = \sum_{p=1}^{|P|} x_p \tau_p, \tag{22}$$

where  $x_p$  is the proportion of the packet flow that was successfully delivered to the receiving router via the  $p$ -th path;  $\tau_p$  is the average delay of packets transmitted along the  $p$ -th path in the ICN;  $|P|$  is the power of the set  $P$ , the value of which determines the total number of paths available for routing.

In the general case, the expression can be used for calculation  $x_p$ :

$$x_p = \frac{\lambda_p}{\lambda^*}, \tag{23}$$

where  $\lambda_p$  is the intensity of the flow of packets that have been successfully delivered to the receiving router via the  $p$ -th path;  $\lambda^*$  is the intensity of the flow of packets that have been successfully delivered to the receiving router using all available paths from the set  $P$ . In the absence of packet loss in ICN  $\lambda^* = \lambda^{(req)}$ .

According to expressions (15)–(19), (21) can write the law of transformation of projections of double covariant tensor  $E$  at change of coordinate systems – from

the basis of edges to the basis of interpolator ways and internal node pairs:

$$E_{\gamma\varepsilon} = (C_{\gamma\varepsilon}^v)^t E_v C_{\gamma\varepsilon}^v. \tag{24}$$

The projection of the metric tensor in the coordinate system of interpolator paths and internal node pairs allows the following decomposition representation:

$$\left\| \begin{array}{c|c} E_{\gamma\varepsilon}^{(1)} & E_{\gamma\varepsilon}^{(2)} \\ \hline \dots & \dots \\ E_{\gamma\varepsilon}^{(3)} & E_{\gamma\varepsilon}^{(4)} \end{array} \right\| = E_{\gamma\varepsilon}, \tag{25}$$

where  $E_{\gamma\varepsilon}^{(1)}$  is the square submatrix of size  $\kappa \times \kappa$ ;  $E_{\gamma\varepsilon}^{(4)}$  is the square submatrix of size  $\vartheta \times \vartheta$ ;  $E_{\gamma\varepsilon}^{(2)}$  is the submatrix of size  $\kappa \times \vartheta$ ;  $E_{\gamma\varepsilon}^{(3)}$  is the submatrix of size  $\vartheta \times \kappa$ .

Then, as a result of the transformations in (24), taking into account (20) and (25), an expression is obtained to calculate the average end-to-end packet delay in ICN (22), which corresponds  $T_a$  in physical content to expression (9):

$$\tau_{MP} = \frac{1}{\lambda^*} (\Lambda_\gamma^t E_{\gamma\varepsilon}^{(1)} \Lambda_\gamma + \Lambda_\varepsilon^t E_{\gamma\varepsilon}^{(2)} \Lambda_\varepsilon). \tag{26}$$

In terms of the described basic model (2), the expression for calculating the probability of loss of packets of the  $k$ -th flow in the ICN can be represented as follows:

$$p_d^k = 1 - b^k. \tag{27}$$

It is important to note that for the calculation of R-factor (8) the physical content of the  $p_d^k$  corresponds to the  $P_{pl}$  value in model (8)–(10).

The projections of the metric tensors  $E$  and  $G$  depend on the values of the route variables as follows:

$$\lambda_z = \sum_{k \in K} \lambda_k^{(req)} x_{i,j}^k \quad \text{and} \quad \lambda_v^z = \lambda_k^{(req)} x_{i,j}^k (1 - p_{i,j}^k). \tag{28}$$

Expressions (28) determine the flux intensities (aggregate and separate  $k$ -th) in the same ICN communication link, which is modelled by an edge  $v_z$  within the end-to-end numbering.

To ensure the adaptability of routing solutions in this work, the criterion of optimality is chosen as a minimum of the following linear objective function:

$$J = \sum_{k \in K} \sum_{w_{i,j} \in W} h_{i,j}^x \lambda_k^{(req)} x_{i,j}^k, \tag{29}$$

where  $h_{i,j}^x$  is the routing metric of the link that connects the  $i$ -th and  $j$ -th ICN routers and displays various functional parameters of this link.

Thus, the problem of adaptive routing in the information communication network with the provision of QoE by the R-factor is formulated in the optimization form. The criterion for the optimality of route solutions was a minimum of linear form (29), and restrictions-expressions (1), (2), (4) and (8).

This optimization problem belongs to the class of non-linear programming problems, for the solution of which there is a wide range of methods. In this study, the MatLab package was used to solve the formulated optimization problem, using interior-point, sequential quadratic programming (SQP), or trust-region-reflective algorithms to solve constrained problems.

**6.3. Research of the tensor model of adaptive routing with providing quality of experience by the R-factor.** To assess the adequacy and effectiveness of the developed tensor model of adaptive routing with QoE by the R-factor, which is represented by expressions (1)–(29), a study was conducted for a fragment of the infocommunication network, which is shown in Fig. 1. The network consisted of nine routers and twelve communication links, the gaps of which indicate their bandwidth (1/s). The operation of each of the router interfaces was simulated by the  $M/M/1/N$  queuing system, and the buffer capacity was 30 packets ( $N=30$ ). The intensity of traffic coming to the network on the first router  $R_1$  and intended for the ninth router  $R_9$  was 350 1/s.

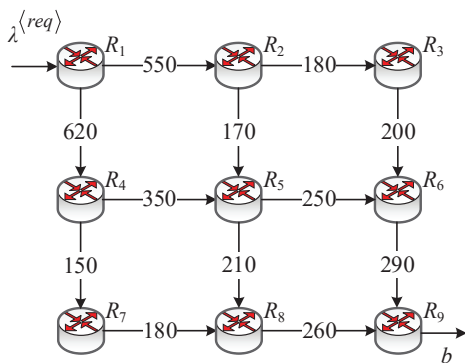


Fig. 1. The investigated fragment of the infocommunication network

Requirements for the level of QoE were set by the R-factor, according to expression (8) and data, according to [13, 14], are shown in Table 1.

Table 1

The relationship between the value of the R-factor and quality of experience [14]

R-value	User satisfaction
90	Very satisfied
80	Satisfied
70	Some users are not satisfied
60	Many users are not satisfied
50	Almost all users are dissatisfied

For clarity, according to the tensor geometrization of the network, in Fig. 2 presents the definition for the network  $S$  of basic internal node pairs, when the poles were nodes  $u_i$  (router  $R_i$ ) and  $u_9$  (router  $R_9$ ), and the main structural characteristics took the following values:  $n=12$ ,  $\kappa(S)=5$ ,  $\vartheta(S)=7$ .

Suppose that the following interpolator paths acted as bases on the network structure (Fig. 2):

- $\gamma_1: u_1 \rightarrow u_2 \rightarrow u_3 \rightarrow u_6 \rightarrow u_9;$
- $\gamma_2: u_1 \rightarrow u_4 \rightarrow u_7 \rightarrow u_8 \rightarrow u_9;$
- $\gamma_3: u_1 \rightarrow u_2 \rightarrow u_5 \rightarrow u_6 \rightarrow u_9;$
- $\gamma_4: u_1 \rightarrow u_2 \rightarrow u_5 \rightarrow u_8 \rightarrow u_9;$
- $\gamma_5: u_1 \rightarrow u_4 \rightarrow u_5 \rightarrow u_8 \rightarrow u_9.$

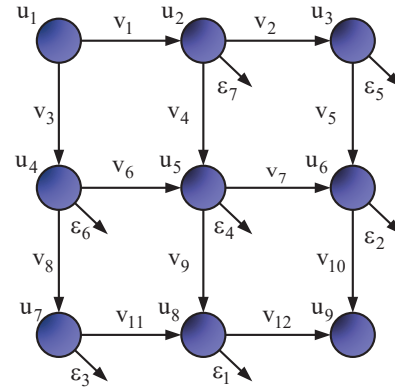


Fig. 2. An example of a one-dimensional network  $S$ , which simulates the structure of the infocommunication network, and the definition of basic interpolator paths and internal node pairs

Further, a study of the influence of the level of QoE requirements on the nature of routing decisions was conducted when routing the flow with an intensity of  $\lambda^{(req)} = 350$  1/s. The values of R-factor varied from 50 to 90 (Table 1).

The characteristics of the calculated paths and the level of QoS, which provided in terms of R-factor, average end-to-end delay and the probability of packet loss in ICN, are presented in detail in Table 2.

It should be noted that as a result of calculations it is established, that the proposed model adaptive routing in the ICN ensure compliance with the requirements regarding the level of QoE, that is, for all cases, the calculated values of the R-factor coincided with the requirements  $R_{(req)}$ .

The adaptive nature of routing solutions was determined by the fact that with the increase in the level of QoE-requirements, the amount of network resource involved increased, for example, the number of used paths, and, accordingly, the bandwidth of ICN communication links. If the minimum acceptable QoE-requirements, i. e. when  $R_{(req)} = 50$  it was necessary to use only two routes (Table 2), then at  $R_{(req)} = 75$  three routes were already involved. With further growth of requirements ( $R_{(req)} = 90$ ), four paths and the corresponding link resource should be used (Table 2).

Table 2

The results of QoE-level calculations for the R-factor

Calculated paths		$\lambda_p, 1/s$	$\tau_p, ms$	$p_d$	$\tau_{MP}, ms$	$b, 1/s$
$H = R_{(req)} = 50$						
1	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R6 \rightarrow R9$	225.8831	98.8	0.0359	87.3	337.4486
2	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R8 \rightarrow R9$	111.5655	63.8			
$H = R_{(req)} = 75$						
1	$R1 \rightarrow R2 \rightarrow R3 \rightarrow R6 \rightarrow R9$	23.4593	33.2	0.0102	67.7	346.4335
2	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R6 \rightarrow R9$	215.1730	80.3			
3	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R8 \rightarrow R9$	107.8011	49.9			
$H = R_{(req)} = 90$						
1	$R1 \rightarrow R2 \rightarrow R3 \rightarrow R6 \rightarrow R9$	28.8131	30.8	0.0015	49.4	349.4754
2	$R1 \rightarrow R2 \rightarrow R5 \rightarrow R6 \rightarrow R9$	21.013	45.1			
3	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R6 \rightarrow R9$	179.4199	58.7			
4	$R1 \rightarrow R4 \rightarrow R5 \rightarrow R8 \rightarrow R9$	120.2294	40.6			

## 7. SWOT-analysis of research results

*Strengths.* In comparison with analogues, thanks to the use of the proposed model of adaptive routing, it was possible to provide a given QoE-level in terms of R-factor with minimal use of network resources. Such results were obtained by using an improved tensor approach in the model to obtain updated expressions to calculate the average delay and probability of packet loss.

*Weaknesses.* The main disadvantage of the developed model is the complexity of the mathematical description of ICN, which is associated with its tensor formalization, as well as the need to solve a rather complex optimization problem of the class of nonlinear programming to determine route variables. However, in general, this does not reduce the significance of the obtained result in relation to its scientific and applied value.

*Opportunities.* With the help of the obtained research results it is possible to ensure the fulfilment of the set QoE-requirements in terms of R-factor to the services provided to end users. In this case, the use of the proposed model is characterized by higher efficiency in the load balancing on many routes in the ICN. This was evidenced by the fact that at a given level of quality rating, with increasing intensity of traffic coming to the ICN, there was a gradual increase in the number of routes involved. That is, the network resource was distributed gradually and more efficiently by 7–10 % relative to the known analogues, which when solving the same problem, immediately use all available routes.

*Threats.* Implementation of the proposed flow-based model of adaptive routing with QoE-level provision on the R-factor indicator is currently a difficult task that requires revision of modern routing protocols for full implementation in a modern infocommunication network.

## 8. Conclusions

1. During the study, the flow-based routing model (1)–(7) was chosen as a basis, which took into account the probable packet losses caused by congestion of network elements. This model was represented by the conditions of implementation of the multipath routing strategy (1), flow conservation (2) and prevention of congestion of communication links (4).

2. To obtain in analytical form the conditions for providing QoE by the R-factor (8), a tensor description of the infocommunication network (11)–(28) was performed. This allowed to obtain analytical expressions for calculating the average end-to-end delay (26) and the probability of packet loss (27), which were used to form QoE conditions (8).

3. To conduct the study, the problem of adaptive routing in the infocommunication network with the provision of QoE-level by the R-factor was formulated in optimization form. In the framework of the proposed model (1)–(28), the solution of the technological problem of adaptive routing was reduced to solving the optimization problem of nonlinear programming based on route variables (1).

The criterion for the optimality of route solutions was a minimum of linear form (29) with the corresponding restrictions (1), (2), (4) and (8). As the results of the study showed (Table 2), the use of the optimality criterion (29) allowed to ensure the adaptive nature of route solutions. This was confirmed by the fact that as the QoE

requirements increased, the volume of network resources used increased – the number of routes and the bandwidth of communication links.

4. To assess the adequacy and effectiveness of the developed tensor model of adaptive routing with the provision of QoE-level by R-factor, a study was conducted for a fragment of the infocommunication network. As a result of calculations, it was found that the proposed model of adaptive routing met the QoE-requirements, i. e. for all cases, the calculated values of the R-factor coincided with the requirements  $R_{(req)}$ . The adaptive nature of routing solutions was determined by the fact that with the increase in the level of QoE-requirements, the amount of network resource involved increased, for example, the number of used paths, and, accordingly, the bandwidth of ICN communication links. Thus, the study on a fragment of the infocommunication network allowed to assess the adequacy and effectiveness of the proposed approach.

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