В роботі запропоновано вирішення актуального питання щодо забезпечення необхідного рівня якості сприйняття в інфокомунікаційній мережі, яке полягає в розробці математичної моделі багатошляхової QoE-маршрутизації із забезпеченням необхідного рейтингу якості. При цьому розрахунок рейтингу якості потребує введення в математичну модель маршрутизації додаткових умов для отримання показників середньої міжкінцевої затримки та ймовірності втрат пакетів. Для цього є доцільним використання тензорної формалізації даних умов при реалізації багатошляхової стратегії маршрутизації. Саме такий спосіб розширення математичних моделей (введення додаткових аналітичних умов) є більш гнучким і дозволить у повній мірі враховувати всю складність взаємозв'язку мережних параметрів в межах QoE. Виходячи з цього, якість сприйняття передачі мови визначається не такими абсолютними значеннями затримок і ймовірностей втрат, оскільки їх взаємозв'язком. В результаті дослідження запропонованої моделі розраховано кількісний показник рейтингу якості, який в порівнянні з рекомендованими показниками згідно існуючих рекомендацій дозволяє оцінити виконання заданого рівня QoE. Тобто при заданій інтенсивності трафіку в мережі розраховані показники середньої міжкінцевої затримки та ймовірність втрат пакетів дозволяють оцінити якість сприйняття завдяки розрахунку рейтингу якості та свідчать про працездатність запропонованого рішення. Та навпаки, завдяки розробленої моделі QoE-маршрутизації представляється можливим контролювати ймовірність втрат і середню міжкінцеву затримку пакетів в інфокомунікаційній мережі, щоб забезпечити виконання заданих QoE-вимог. Також в роботі проведено порівняльний аналіз із потоковою моделлю багатошляхової маршрутизації, яка базується на використанні метрики IGRP, що дозволив оцінити ефективність запропонованого рішення та продемонстрував виграш щодо рейтингу якості від 12 до 25 % в залежності від вихідних даних

Ключові слова: інфокомунікаційна мережа, якість сприйняття інфокомунікаційної послуги, середня міжкінцева затримка, ймовірність втрат пакетів, тензор, маршрутизація, рейтинг якості

UDC 621.391
DOI: 10.15587/1729-4061.2018.141989

DEVELOPMENT OF THE TENSOR MODEL OF MULTIPATH QOE-ROUTING IN AN INFOCOMMUNICATION NETWORK WITH PROVIDING THE REQUIRED QUALITY RATING

O. Lemeshko
Doctor of Technical Sciences*
E-mail: oleksandr.lemeshko.ua@ieee.org
M. Yevdokymenko
PhD*
E-mail: marina.ievdokymenko@nure.ua
Naors Y. Anad Alsaleem
PhD
Department of Computer science
University of AL-Hamdaniya
Ninavah, 79CF+PV, Bakhdida, Hamdaniya, Iraq
E-mail: nawrasyounis@yahoo.com
*Department of Infocommunication engineering
Kharkiv National University of Radio Electronics
Nauky ave., 14, Kharkiv, Ukraine, 61166

1. Introduction

The current trend of convergence of networks of different types, the increase in the volume of traffic, the emergence of multimedia applications running in real time, necessitates ensuring the end-to-end quality of service (Quality of Service, QoS). To date, there exist several approaches to ensure QoS (A1–A3):

– A1: based on the use of routing metrics of communication channels, interconnected through QoS-indicators;

– A2: based on the implementation of technology of Traffic Engineering (TE), which focuses on the effective load balancing along an infocommunication network;

– A3: through the implementation of a multipath routing while ensuring the required QoS indicators.

When analyzing these approaches, it is worth noting that A1 and A2 are focused only on improving the quality of service in an infocommunication network in general and give no warranties regarding the numerical values for the main indicators of QoS. In contrast to the first two approaches, the third approach is aimed precisely at calculating the routes that guarantee the specified values of such QoS metrics as the packet transfer rate, average end-to-end delay, the probability of packet loss, etc. The given approaches largely determine the quality of network performance (NP). However, in practice, ensuring QoS is defined, taken all together, by the quality of network performance (NP) and the quality of experience (QoE) at the user level. In this case, providing the required level of QoE is central and essential in order to optimize the income and resources of the provider/operator.

2. Literature review and problem statement

To analyze existing solutions in the field of ensuring QoE-metrics, it is necessary first to consider the mechanisms of their estimation. It is known that each type of the transmitted traffic (voice, video, data) employs two types of methods for evaluating the quality of experience (QoE): subjective [1–4] and objective [5–7] (Fig. 1). However, each of the specified methods is applied only for a certain type of traffic. Moreover, the use of each method is limited by a possibility to implement it within existing technological solutions.

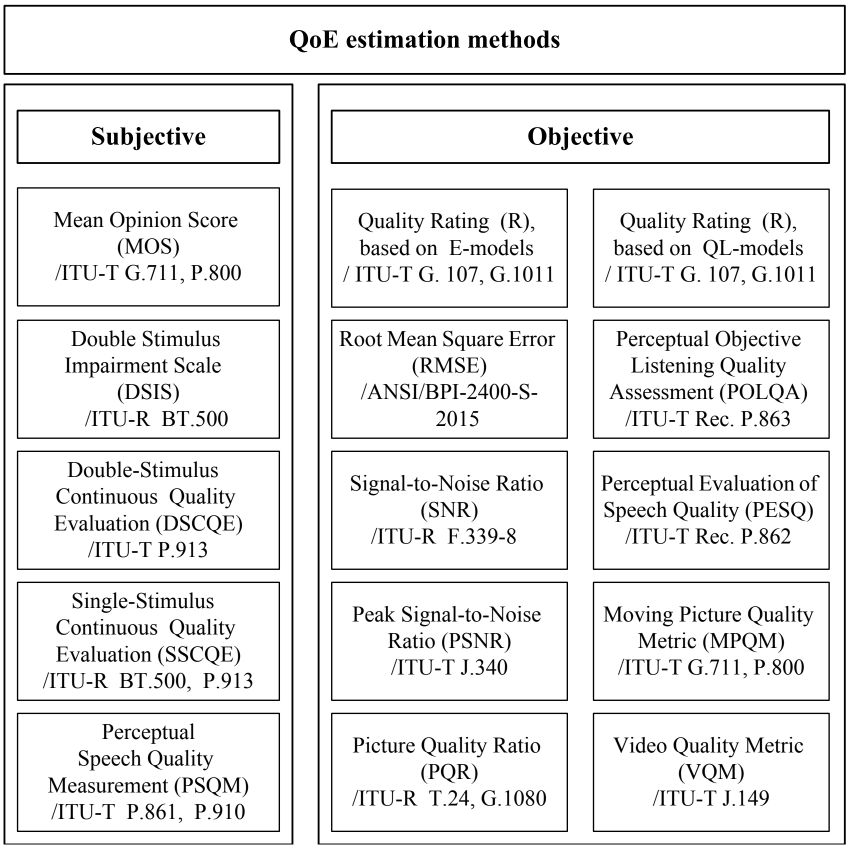

Fig. 1. Classification of methods for evaluating the quality of experience

It is known that the subjective rating of perceived quality yields only the integral evaluation of quality indicators for the transmitted video and audio traffic. A given method of evaluation is used mainly at a point in time when the transmitted audio and video information undergoes distortions arising in the process of digitizing, compressing, transmitting, decoding, etc. That makes the subjective evaluation of perceived quality a very laborious process associated with considerable time cost. Thus, authors in paper [8], in order to evaluate the video stream in line with the standard ITU-R BT.500-8-11, employed subjective metrics Single-Stimulus Continuous Quality Evaluation (SSCQE), Double Stimulus Impairment Scale (DSIS) and Double Stimulus Continuous Quality Scale (DSCQS). These metrics exploit the features of human vision and make it possible to estimate, based on a five-point scale, the differences between the original and the distorted video footage using static algorithms. The disadvantage of a given approach is the labor-intensity of experimental subjective assessment and time cost, which is unacceptable for applications running in real time.

There are also papers [9, 10], which, in order to assess the quality of experience; apply the method of Mean Opinion Score (MOS). However, an analysis that was conducted revealed that a given method does not make it possible to quantitatively consider the factors that affect the quality of service, specifically does not take into consideration the end-to-end delay and losses of packets. Therefore, the application of this method in modern networks does not make it possible to execute quality control in real time and respond timely to potential problems in a network. In addition, the main drawback of a given method is the consumption of additional network resources, and the need for specific settings of network equipment.

To receive an objective assessment of quality, paper [11] proposes using the Q-learning mechanism based on a pseudo-subjective quality assessment (PSQA). A given mechanism is based on selecting the best path based on the comparison of indicators for the rate of transmission and packet losses in the network. In addition, there are a number of studies [12] aimed at ensuring QoE in terms of the type of transmitted traffic (video, data, voice, etc.), but these approaches do not make it possible to manage network resources.

The basis of objective methods could be formed by the E-model presented in [13] that relates to the measurement of characteristics of terminals and networks in accordance with recommendations from [14–16]. A given evaluation method takes into consideration the structural-functional characteristics of infocommunication networks, as well as more than twenty different parameters to define the Transmission Rating Factor (R-Factor). The range of the measured parameters include, for example, a travel time of the signal, delay variation (Jitter), packet loss and packet loss peaks (Bursts). In this case, the result of calculations in accordance with the E-model is the Quality Rating (QR). QR defines the quality level in a network and makes it possible to combine into a single indicator both the individual characteristics of signals and the network transmission parameters (delay and magnitude of packet losses in a network). However, the main shortcoming of this direction is the lack of a direct relationship between network settings and a quality rating.

All the above-specified QoE assessment methods are used to ensure quality of service in infocommunication networks and typically underlie the mathematical models of routing aimed to effectively manage network resources. However, one of the most effective means to ensure the required QoE in infocommunication networks is the application of a multipath routing strategy. Thus, papers [17–19] suggest approaches to using the routing models in order to ensure service quality for a variety of network performance indicators: average delay, the probability of losses, and the packet transmission rate. However, in the context of ensuring QoE, a given approach makes it possible to calculate the separate network parameters only (for example, an average delay or the probability of loss) with further assessment bases on a quality rating. Therefore, to date, it is necessary to develop the direction of ensuring the QoE-indicators with simultaneous control based on the indicators of an end-to-end delay and packet losses. These very indicators have a direct impact on the quality of experience of the service provided to the end user. Given this, to describe the structural-functional characteristics of an infocommunication network, it is advisable to also use a traditional mathematical model of the multipath routing, but with the introduction of conditions for ensuring such QoE-metrics as an end-to-end delay and a packet loss probability. At the same time, the introduction of these conditions is possible only owing to their tensor formalization that would enable obtaining the mathematical expressions that relate the above indicators. Thus, the study to be conducted would make it possible to satisfy the QoE requirements (according to a quality rating) using the multipath routing with control over an average end-to-end delay and the packet loss level.

3. The aim and objectives of the study

The aim of this work is to ensure the predefined quality rating using the multipath QoE-routing with control over indicators of an average end-to-end delay and packet losses in a network.

To accomplish the aim, the following tasks have been set:

– to select a flow model of the multipath QoE-routing to account for the indicators of an end-to-end delay and a packet loss probability;

– to perform the tensor formalization of a model of the multipath QoE-routing in order to analytically describe the relationship between indicators of an end-to-end delay and a packet loss probability;

– to study experimentally the proposed flow model of the multipath QoE-routing to estimate its effectiveness in comparison with the traditional flow model based on using the IGRP metric.

4. A flow model of the multipath QoE-routing with respect to the indicators of an end-to-end delay and a packet loss probability

Within the proposed model, the structure of an infocommunication network is described using a one-dimensional network $S=(U, V)$, where $U=\left\{u_i, i=\overline{1,m}\right\}$ is the set of zero-dimensional simplexes – the nodes (routers) of the network,

$$V=\left\{v_z=(i,j);\ z=\overline{1,n};\ i,j=\overline{1,m};\ i\neq j\right\}$$

is the set of one-dimensional simplexes – the edges of the network, where edge $V_z=(i,j)$ models the z-th communication link that connects the i-th and j-th ICN routers via the appropriate j-th interface, and U_i^* is the subset of routers that are incidental to routers U_i. Then, to implement a multipath routing, it is necessary to ensure the calculation of route variables $x_{i,j}^k$ which characterize the intensity share of the k-th flow along link (i,j). The route variables are superimposed with the following conditions:

$$0\le x_{i,j}^k\le 1. \qquad (1)$$

The conditions for flow conservation on the network routers, taking into consideration the possible packet losses caused by overloading the queue buffer, within the proposed routing model, take the form [19]:

$$\begin{cases}\sum\limits_{j:(i,j)\in V} x_{i,j}^k=1 & \text{if } k\in K,\ i=s_k;\\ \sum\limits_{j:(i,j)\in V} x_{i,j}^k-\sum\limits_{j:(j,i)\in V} x_{j,i}^k(1-p_{j,i}^k)=0 & \text{if } k\in K,\ i\neq s_k,d_k;\\ \sum\limits_{j:(j,i)\in V} x_{j,i}^k(1-p_{i,j}^k)=\varepsilon^k & \text{if } k\in K,\ i=d_k,\end{cases} \qquad (2)$$

where K is the set of flows in the network; s_k is the router-sender; d_k is the router-receiver for packets from the k-th flow; ε^k is the share of the k-th flow serviced by the network, that is, whose packages were successfully delivered to the router-receiver; $p_{i,j}^k$ is the packet loss probability of the k-th flow at the j-th interface of the i-th router.

If the work of the j-th interface of the i-th router is modeled by the mass service system with failures of the type M/M/1/N, then the probability of packet loss in the k-th flow could be calculated as follows:

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

where $\rho_{i,j}=\dfrac{\lambda_{i,j}}{\varphi_{i,j}}$ is the coefficient of utilization of the j-th interface at the i-th router; N is the maximum number of packets in the queue; $\lambda_{i,j}$ is the flow intensity in the link $(i,j)\in V$, 1/c; $\varphi_{i,j}$ is the bandwidth of the j-th interface of the i-th router.

The intensity of the flow in the link, taking into consideration the possible losses of packets, is then calculated as

$$\lambda_{i,j}=\sum_{k\in K}\lambda_k^{\langle req\rangle}x_{i,j}^k(1-p_{i,j}^k), \qquad (4)$$

where $\lambda_k^{\langle req\rangle}$ is the average intensity of the k-th flow arriving to the network to be serviced, which assigns the QoS-requirements for the package transmission rate.

In order to manage the process to eliminate the overload of links and queues, the structure of the model is introduced with the following constraints [20]:

$$\sum_{k\in K}\lambda_k^{\langle req\rangle}x_{i,j}^k(1-p_{i,j}^k)<\varphi_{i,j}\quad \text{at } (i,j)\in V. \qquad (5)$$

In a general form, the QoE-requirements for the transmission of voice at the predefined type of terminal equipment and the codec used, in accordance with the recommendations G.109 and Y.1540 [14–16], could be recorded as follows:

$$R\ge R_{req}\ \text{ at }\ R=R_0-I_{dd}(T_a)-I_{e-eff}(P_{pl}), \qquad (6)$$

where $I_{dd}(T_a)$ is the coefficient of quality reduction, caused by the long delay, as a function of the network delay, and $I_{e-eff}(P_{pl})$ is the coefficient of quality reduction, caused by losses of voice packets, determined by the following expressions:

$$I_{dd}(T_a)=\begin{cases}0, & T_a\le 100\text{ ms};\\ 25\left[\left(1+X^6\right)^{\frac{1}{6}}-3\left(1+\left[\dfrac{X}{3}\right]^6\right)^{\frac{1}{6}}+2\right], & T_a>100\text{ ms};\end{cases} \qquad (7)$$

$$I_{e-eff}(P_{pl}) = I_e + (95 - I_e)\frac{P_{pl}}{\frac{P_{pl}}{BurstR} + B_{pl}}, \quad (8)$$

where $X = \log\frac{\left(\frac{T_a}{100}\right)}{\log 2}$; I_e is the coefficient of quality reduction, due to the use of low-speed codecs [16]; T_a is the average end-to-end packet delay in the network P_{pl} is the total probability of packet losses in the network. B_{pl} is the factor that takes into consideration the resistance of the codec to losses [15]; *Burst* is the coefficient of "burst" in losses.

When satisfying conditions (6) with respect to (7) and (8), it is important to have mathematical expressions that analytically describe the relationship between route variables (1), traffic characteristics, network settings, the indicators of end-to-end delay T_a and packet loss probability P_{pl}. Taking into consideration the results obtained in papers [13, 19], it is appropriate to apply the functional of tensor modeling of routing processes in infocommunication networks.

5. Tensor formalization of multipath QoE-routing model

In accordance with the methodology for tensor modeling ICN, proposed in papers [13, 19, 21], a network structure defines the anisotropic space formed by the set of contours and nodal pairs. The dimensionality of this space is determined by the total number of edges in the network and equals n. In this case, each independent path (a edge, a circuit, or nodal pair) defines the coordinate axis in the spatial structure. Typically, ICN is modeled by a connected one-dimensional network, that is, it contains one linked component, and then a cyclomatic number μ and rank ϕ of the network define, respectively, the number of basis contours and nodal pairs, for which the following expressions hold:

$$\mu = n - m + 1, \quad \varphi = m - 1, \quad n = \varphi + \mu. \quad (9)$$

In the selected space, when transmitting packets from each k-th flow, ICN could be represented by a mixed bivalent tensor

$$Q = T \otimes \Lambda, \quad (10)$$

where ⊗ is the operator of tensor multiplication while the components of tensor Q are a univalent covariant tensor of average delay of packages T and a univalent contravariant tensor of flow intensities Λ in the coordinate paths of the network. Therefore, index k is omitted in the course of tensor description of the network.

Under the proposed model (1)–(5) when the interface is modeled by the queuing system with failure of the type M/M/1/N, the average delay of packets in an arbitrary communication channel ICN is approximated by expression

$$\tau = \frac{\rho - \rho^{N+2} - (N+1)\rho^{N+1}(1-\rho)}{\lambda\left(1-\rho^{N+1}\right)(1-\rho)}. \quad (11)$$

In this case, in accordance with the postulate of G. Krohn's second generalization [21] based on results from paper [13, 17], expressions (11), recorded for each link in the network, define the following vector-matrix equation:

$$\Lambda_v = G_v T_v, \quad (12)$$

where Λ_v and T_v are the projections, respectively, of tensor Λ and tensor T in the coordinate systems of edges, represented by the n-dimensional vectors of flow intensities and a average delay of packets in communication links; $G_v = \left\| g_v^{ij} \right\|$ is the diagonal $n \times n$ matrix whose elements correspond to the edges of the network and are calculated from expression [21]

$$g_v^{ii} = \frac{\left(1-\left(\rho_i^v\right)^{N_i^v+1}\right)\left(1-\rho_i^v\right)\left(\lambda_i^v\right)^2}{\rho_i^v - \left(\rho_i^v\right)^{N_i^v+2} - \left(N_i^v+1\right)\left(\rho_i^v\right)^{N_i^v+1}\left(1-\rho_i^v\right)}. \quad (13)$$

Projections of tensors of the average delays of packets and the flow intensities in the coordinate system of contours and nodal pairs are linked via expression similar to expression (12):

$$\Lambda_{\pi\eta} = G_{\pi\eta} T_{\pi\eta}. \quad (14)$$

According to the reverse tensor attribute, tensor G is the double contravariant metric tensor, whose projections at a change in the coordinate system of its consideration are transforms as follows:

$$G_{\pi\eta} = A^t G_v A, \quad (15)$$

where $G_{\pi\eta}$ is the projection of tensor G in the coordinate system of contours and nodal pairs; A is the $n \times n$ matrix of covariant transformation; $[\cdot]^t$ is the transposition operation. As shown in [19], matrix $G_{\pi\eta}$ could be represented by a block structure, that is,

$$G_{\pi\eta} = \left\| \begin{array}{c|c} G_{\pi\eta}^{\langle 1\rangle} & G_{\pi\eta}^{\langle 2\rangle} \\ \hline G_{\pi\eta}^{\langle 3\rangle} & G_{\pi\eta}^{\langle 4\rangle} \end{array} \right\|, \quad G_{\pi\eta}^{4} = \left\| \begin{array}{c|c} G_{\pi\eta}^{\langle 4,1\rangle} & G_{\pi\eta}^{\langle 4,2\rangle} \\ \hline G_{\pi\eta}^{\langle 4,3\rangle} & G_{\pi\eta}^{\langle 4,4\rangle} \end{array} \right\|,$$

where $G_{\pi\eta}^{\langle 1\rangle}$ and $G_{\pi\eta}^{\langle 4\rangle}$ are the square submatrices of dimension μ×μ and ϕ×ϕ, respectively, $G_{\pi\eta}^{\langle 2\rangle}$ is the submatrix of dimension μ×ϕ, $G_{\pi\eta}^{\langle 3\rangle}$ is the submatrix of dimension ϕ×μ; $G_{\pi\eta}^{\langle 4,1\rangle}$ is the first element of matrix $G_{\pi\eta}^{\langle 4\rangle}$; $G_{\pi\eta}^{\langle 4,2\rangle}$ is the second element of matrix $G_{\pi\eta}^{\langle 4\rangle}$ of dimension 1×(ϕ–1); $G_{\pi\eta}^{\langle 4,3\rangle}$ is the third element of matrix $G_{\pi\eta}^{\langle 4\rangle}$ of dimension (ϕ–1)×1; and $G_{\pi\eta}^{\langle 4,4\rangle}$ is the fourth element of matrix $G_{\pi\eta}^{\langle 4\rangle}$ of dimension (ϕ–1)×(ϕ–1).

Within the framework of tensor description of an infocommunication network under conditions of implementing the multipath routing strategy [13, 17, 19–21], the probability of packet delivery P_{pl} and the average end-to-end delay T_a could be calculated as:

$$P_{pl} = \frac{\sum_{j=2}^{\varphi}\lambda_\eta^j}{\lambda^{\langle req\rangle}}, \quad (16)$$

$$T_a = \frac{\lambda^{\langle req\rangle}\varepsilon - G_{\pi\eta}^{\langle 4,2\rangle}\left[G_{\pi\eta}^{\langle 4,4\rangle}\right]^{-1}\Lambda_{\eta-1}}{\left(G_{\pi\eta}^{\langle 4,1\rangle} - G_{\pi\eta}^{\langle 4,2\rangle}\left[G_{\pi\eta}^{\langle 4,4\rangle}\right]^{-1}G_{\pi\eta}^{\langle 4,3\rangle}\right)}, \quad (17)$$

where $\Lambda_{\eta\text{-}1}$ is the vector of intensities of lost packets at the interfaces of routers whose coordinates are determined from expression

$$\lambda_{\eta}^{i}=\sum_{j=1}^{U_i^*}\lambda^{\langle req\rangle}x_{i,j}p_{i,j} \qquad (18)$$

and express, for each i-th router, the intensity of packet losses, total for its all interfaces.

When solving the problem on the multipath QoE-routing, the following condition was chosen as the criterion of optimality for obtained solutions:

$$\max_{x,\varepsilon}\left[\sum_{k\in K}\lambda_k^{\langle req\rangle}\varepsilon^k\right]. \qquad (19)$$

The application of a given criterion would maximize the overall performance of the info-communication network.

6. Comparative analysis of the proposed model of multipath QoE-routing and a flow model based on the IGRP metric

To assess the effectiveness of the proposed solution, hereinafter referred to as "model 1", in this work we performed a comparative analysis with the flow model ("model 2"). In this case, model 2 is based on the use of the IGRP metric and is represented by a system of linear algebraic equations of the state of an infocommunication network [22].

Within the framework of model 2, chosen for comparison, the optimality criterion was a minimum of the sum of weighted coefficients of using separate links of communication [23]

$$\min_{x}\sum_{k\in K}\sum_{(i,j)\in V}c_{i,j}x_{i,j}^{k}, \qquad (20)$$

where $c_{i,j}$ is the weight factor calculated based on a throughput of communication link (i, j) by analogy with the EIGRP protocol metric ($c_{i,j}=10^7/\varphi_{i,j}$).

To visualize the results obtained, we shall solve the problem for a fragment of the info-communication network shown in Fig. 2.

Fig. 2 shows that the network consists of five routers and six links; communication links gaps exhibit their throughput (1/s). The load of the network is understood as the ratio of traffic intensity, entering the network, to its throughput. In this connection, the intensity of the flow entering the network at the first router and intended for the fifth router changed from zero to 310 1/s and the requirements for the QoE level were set by a quality rating R_{req}=70, in line with expression (6) and the data, according to [14], given in Table 1.

The result of solving the problem on multipath routing using model 1, according to (1) to (19) and model 2, according to (20) and (6), (16) to (18), is the order of flow distribution along separate communication links in an info-communication network. The research results are shown in Fig. 3, 4, where the gaps in the communication links exhibit (top down) their throughput capacities (1/s), the intensity of the flow (1/s), and the average packet delay (ms).

Table 1

Relation between quality rating (QR) and the quality of experience by user [14]

Quality rating value, R	User satisfaction
90	Very satisfied
80	Satisfied
70	Some users are not satisfied
60	Many users are not satisfied
50	Almost all users are not satisfied

The main indicator of QoE, based on which we compared model 1 and model 2, was a quality rating, which had to be compared with the preset R_{req}=70, according to expression (6) and data from Table 1. In this case, the quality rating was calculated using the derived indicators of an end-to-end delay (17) and the probability of packet losses in the network (16).

When solving the problem for model 1, we calculated three paths, as well as two paths for model 2, the characteristics of which are given in Table 2.

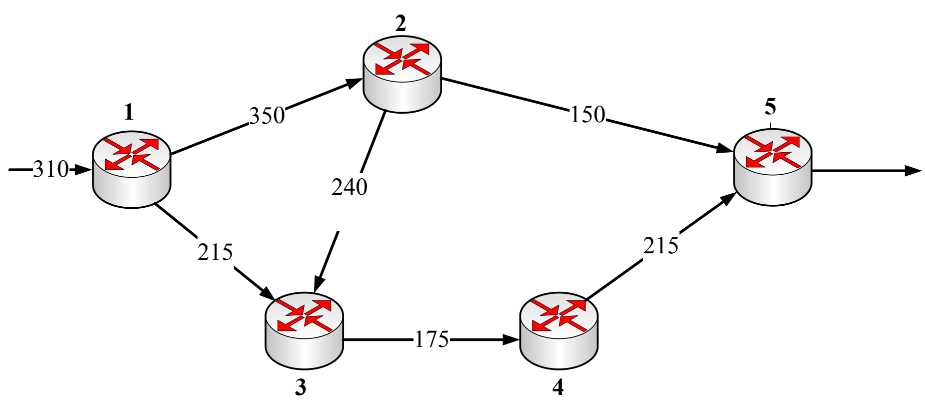

Fig. 2. A fragment of the examined infocommunication network

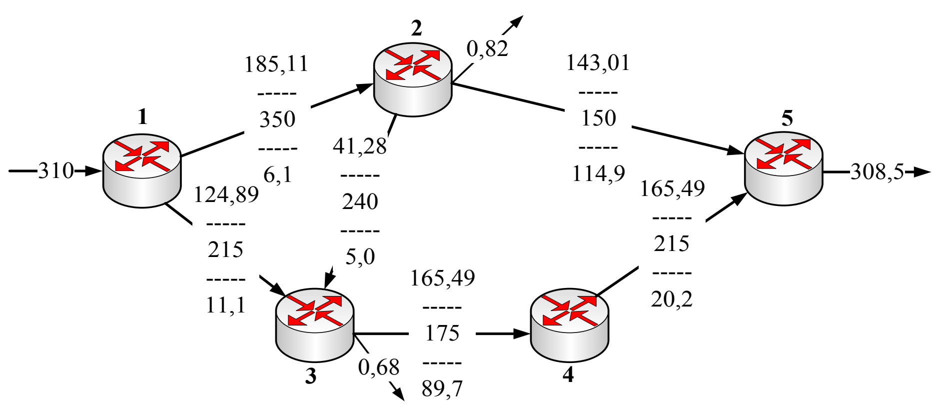

Fig. 3. Solving the problem on multipath routing using model 1

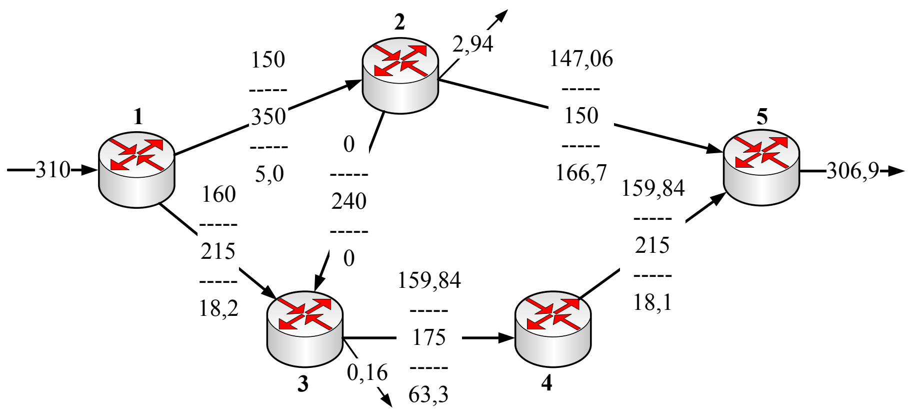

Fig. 4. Solving the problem on multipath routing using model 2

Table 2

Results of a comparative analysis of model 1 and model 2

Calculated paths:	Model 1		Calculated paths:	Model 2	
	Average packet delay, ms	Packet loss proba-bility, %		Average packet delay, ms	Packet loss proba-bility, %
path 1: 1→2→5	121	0.48	path 1: 1→2→5	171.7	1
path 2: 1→2→3→4→5	121	0.48	path 2: 1→3→4→5	99.6	1
path 3: 1→3→4→5	121	0.48	–		

Table 2 shows that when studying the proposed model 1, along each path, the average packet delay was the same and amounted to 121 ms, the probability of packet losses in the network was 0.048. The quality rating R, evaluated using expression (6), amounted to 70.22, which, in accordance with the original data and Table 1, confirmed meeting the requirements regarding the level of QoE. When examining model 2, based on the IGRP metric, the delay along path 1 was 171.7 ms, along path 2 – 99.6 ms, while the average delay amounted to 134.15 ms; the probability of packet losses in the network was 0.01. However, the quality rating *R* amounted to 61.7939, which does not satisfy the conditions of the stated problem, consequently, it does not provide for the predefined values according to Table 1.

In this regard, based on the results of comparative analysis, it can be noted that for a given example, at the same traffic intensity and for the same network structure, the proposed model for the multipath QoE-routing outperforms, in terms of quality rating, by 13.64 %, which confirms the effectiveness of the proposed solution. In addition, for other initial data, the model for the multipath QoE-routing outperformed by 12 to 25 %.

7. Discussion of results of studying a flow model of the multipath QoE-routing

The aim of examining the proposed model of the multipath QoE-routing was to satisfy the required level of QoE in an infocommunication networks. To this end, based on the derived values for a average end-to-end delay and a packet loss probability (Table 2), we calculated the principal indicator of QoE – a quality rating, which amounted to R=70.22. Next, the result was compared to the predefined quality rating of R_{req}=70 from Table 1 [14], which meant that only some users were not satisfied with the service provided by the communication network. Thus, the use of a given model makes it possible to assess if the QoE requirements are satisfied based on a quality rating through the indicators of delay and packet loss. The performed comparative analysis of the proposed model to a flow model based on the IGRP metric has proven its effectiveness, as evidenced by outperforming a quality rating by 13.64 %.

The benefit of our proposal is the presence of a formalized relationship between assessments of service quality that makes it possible to synthesize control over network parameters based on the requirements of the end-users, stated in the form of the integral estimates for perceived quality. Such a technique to expand mathematical models for rendering services of guaranteed quality is more flexible and makes it possible to fully account for the complexity of relationship between network parameters within the framework of QoE.

In addition, the advantage of using tensor constraints is their orientation towards the multipath routing with balancing the traffic along all available routes, taking into consideration the flow character of traffic, a possibility to perform specified requirements for each indicator of the quality of experience separately, which more fully meets the concept of QoE-routing.

The disadvantage of using tensor formalization is the complication of the routing model and the enhanced scalability of solutions because the problem takes a nonlinear form. However, given the application of SDN-networks, the routing task could be solved not at separate routers, whose processing power is rather limited, but at high-performance SDN-controllers or an entire cluster of such controllers.

It is worth noting that the further development of the proposed solution implies ensuring the quality of experience when providing not only the VoIP services, but other infocommunication services as well (for example, IPTV).

8. Conclusions

1. We propose a mathematical model of the multipath QoE-routing in an infocommunication network that ensures the required quality rating. The main goal was to account for the indicators of an end-to-end delay and a packet loss probability with the subsequent evaluation of the quality rating at the user level. We also selected the criterion of optimality responsible for the maximum overall performance in an infocommunication network in the presence of constraints for maintaining the flow, for the absence of communication link overload and the execution of the QoE-requirements.

2. The novelty of the proposed solution is the tensor formalization of the selected model of routing, owing to which we managed to derive mathematical expressions in the analytical form, which bind the indicators of an end-to-

end delay and a packet loss probability in order to satisfy the QoE-requirements. That made it possible to improve the adequacy of an infocommunication network description, as well as the consistency of solutions to control traffic while maintaining the QoE metrics.

3. We have experimentally investigated the proposed model for the multipath QoE-routing at an infocommunication network fragment. The result was a comparison between the derived value for a quality rating, which totaled 70.22, and the recommended rating Rreq=70, which, in accordance with the original data and Table 1, confirmed meeting the requirements regarding the level of QoE. To assess the effectiveness of the proposed solution, we ran a comparative analysis of the proposed model to a flow model based on the IGRP metric. The results of solving the problem showed outperforming the rating of quality by 12 to 25 %, depending on the source data.

References

1. ITU-T P.830: Subjective performance assessment of telephone-band and wideband digital codecs. ITU, 1996.
2. ITU-T P.863. Perceptual objective listening quality assessment. ITU, 2014.
3. ITU-T P.911. Subjective audiovisual quality assessment methods for multimedia applications. ITU, 1998.
4. ITU-T P.862. Perceptual evaluation of speech quality (PESQ): An objective method for end-to-end speech quality assessment of narrow-band telephone networks and speech codecs. ITU, 2001.
5. ITU-T P.910. Subjective video quality assessment methods for multimedia application. ITU, 2008.
6. ITU-T P.806. A subjective quality test methodology using multiple rating scales. ITU, 2014.
7. ITU-T G.1011. Reference guide to quality of experience assessment methodologies. ITU, 2015.
8. ITU-R BT.500. Methodology for the Subjective Assessment of the Quality of Television Pictures. ITU, 2011.
9. Bentaleb A., Begen A. C., Zimmermann R. SDNDASH: Improving QoE of HTTP Adaptive Streaming Using Software Defined Networking // Proceedings of the 2016 ACM on Multimedia Conference – MM '16. 2016. P. 1296–1305. doi: https://doi.org/10.1145/2964284.2964332
10. Quality of Experience-based Routing of Video Traffic for Overlay and ISP Networks / Calvigioni G., Aparicio-Pardo R., Sassatelli L., Leguay J., Medagliani P., Paris S. // IEEE INFOCOM 2018 – IEEE Conference on Computer Communications. 2018. P. 935–943.
11. From Packets to People: Quality of Experience as a New Measurement Challenge / Schatz R., Ho feld T., Janowski L., Egger S. // Lecture Notes in Computer Science. 2013. P. 219–263. doi: https://doi.org/10.1007/978-3-642-36784-7_10
12. Mellouk A., Hoceini S., Tran H. A. Quality of Experience for Multimedia: Application to Content Delivery Network Architecture. John Wiley & Sons, 2013. doi: https://doi.org/10.1002/9781118649367
13. Lemeshko O. V., Yeremenko O. S. Dynamics analysis of multipath QoS-routing tensor model with support of different flows classes // 2016 International Conference on Smart Systems and Technologies (SST). 2016. doi: https://doi.org/10.1109/sst.2016.7765664
14. ITU-T G.109. Amendment 1 New Appendix I – The E-model-based quality loops for predicting speech transmission quality and user satisfaction from time-varying transmission impairments. ITU, 2007.
15. ITU-T Y.1540. Internet protocol data communication service – IP packet transfer and availability performance parameters. ITU, 2016.
16. ITU-T G.107. The E-model: A computational model for use in transmission n planning. ITU, 2014.
17. Janevski T., Jankovic M., Markus S. Quality of service regulation manual. Telecommunication development Bureau, 2017. 173 p.
18. Lemeshko A. V., Evseeva O. Y., Garkusha S. V. Research on Tensor Model of Multipath Routing in Telecommunication Network With Support of Service Quality by Greate Number of Indices // Telecommunications and Radio Engineering. 2014. Vol. 73, Issue 15. P. 1339–1360. doi: https://doi.org/10.1615/telecomradeng.v73.i15.30
19. Lemeshko O., Yeremenko O. Dynamic presentation of tensor model for multipath QoS-routing // 2016 13th International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET). 2016. doi: https://doi.org/10.1109/tcset.2016.7452128
20. Lemeshko O., Yevsieieva O., Yevdokymenko M. Tensor flow-based model of quality of experience routing // 2018 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET). 2018. doi: https://doi.org/10.1109/tcset.2018.8336364
21. Kron G. Tensor Analysis of Networks. John Wiley and Sons, 1949. 635 p.
22. Riedl A., Schupke D. A. Routing Optimization in IP Networks Utilizing Additive and Concave Link Metrics // IEEE/ACM Transactions on Networking. 2007. Vol. 15, Issue 5. P. 1136–1148. doi: https://doi.org/10.1109/tnet.2007.902546
23. Lemeshko O., Yeremenko O. Linear optimization model of MPLS Traffic Engineering Fast ReRoute for link, node, and bandwidth protection // 2018 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET). 2018. doi: https://doi.org/10.1109/tcset.2018.8336365