



Model of functioning of the centralized wireless information ecosystem focused on multimedia streaming

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ABSTRACT

The article's highlight is the Markov model of functioning of the centralized wireless information ecosystem focused on multimedia streaming. The model describes the stochastic process of joint service by the base transmission station (BTS) of independent streams of multimedia transfer and text data transfer. To assess the effectiveness of the fulfilment of its purpose by the studied ecosystem, a metric of quality parameters is proposed, in particular: - the percentage of lost requests for multimedia transfer; - the percentage of lost requests for text data transfer; - the average share of the resource of the BTS communication channel involved in the service of multimedia transfers; - the average share of the BTS communication channel involved in the service of text data transfer; - the percentage of censored operating time of the studied system, when the incoming request for multimedia transfer was rejected due to lack of the required share of free resource of the communication channel; - the ratio of the number of lost multimedia transfer requests to the potential number of transfer sessions. The first four parameters are indicators of the reliability of the studied system, and the last two qualitative parameters have a direct economic interpretation. For the studied ecosystem to realize its purpose in conditions of moderate and high load, the model introduced a self-limiting function. This feature allows us to flexibly balance the servicing of transfer sessions of both types, balancing the values of the first two quality indicators. The adequacy of the proposed mathematical apparatus is proved empirically.

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1. Introduction

The leitmotif of the global economy in recent years is the acceleration of science and technology. The World Bank noted, in particular, the emergence of new end-to-end technologies such as digital design, modelling and integration, high-performance computing, 3D printing, additive manufacturing, advanced materials, robotics, and artificial intelligence, Big Data and Advanced Analytics, Internet of Things, augmented and virtual reality, blockchain technologies, industrial biotechnologies, etc.

In developed countries, the creation and implementation of technological and managerial innovations occupy an important place in virtually all economic and social activity areas. Rapidly introduced technologies are becoming increasingly important with growing risks caused by adverse atmospheric, environmental, and biological origin factors. The COVID-19 coronavirus outbreak poses many challenges to the innovation ecosystem and highlights the interconnectedness of both the global and national communities. Thanks to the widespread use of innovation, national economies are finding new ways to support economic growth and ensure a high standard of living. These trends are facilitated by the availability of effective innovation methods, including through technology transfer.

However, the basis of all these tectonic innovation processes is effectively communicating communities, people, and things. It should be borne in mind that people are natural and comfortable communicating in video conferencing, while IoT devices mostly exchange text messages. As the size of these user audiences in today's cyberspace grows exponentially, communication tools

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and their information systems become bottlenecks in the path of progress. Thus, the study of the functioning of a centralized wireless information ecosystem (as a basic link of modern information infrastructure), focused on multimedia streaming, is relevant.

In addition, we note that increasing the level of use of a prepaid information transmission resource in a centralized wireless ecosystem while maintaining the required service standards for incoming traffic flows is an important task, the solution of which is necessary for organizing the effective operation of the target network infrastructure. At the same time, we take into account that the actors in such an ecosystem are the set of clients (including end devices of IoT sensor arrays), on the one hand, and a wireless network infrastructure base station, on the other hand. The processes of information interaction are characterized by stochastic and are independent. To simplify the analytical part of the research, we will consider the considered ecosystem as closed. Let us formulate the problem under study in a descriptive style. It is known [1–5] that when jointly serving narrow-band and broadband traffic of real-time communication applications, there is an uncontrolled redistribution of the channel resource in favour of application flows with low requirements for the information transmission resource. To eliminate the negative consequences of this phenomenon, it is proposed to use either redundancy or separate occupation of the resource of network clusters. For the theoretical substantiation of the procedure for choosing a specific scenario, it is necessary to develop models that describe the consequences of the implementation of these scenarios, as well as methods for calculating the values of the qualitative characteristics of using the information transmission resource. This article is devoted to the solution of these important applied problems.

2. State-of-the-art

The most pressing problem in the field of info-communications is the identification and targeted service of incoming requests. The reliable result of their identity is the basis for the rational choice of means and methods of their effective maintenance. Let us mention only the generally accepted methodologies used to evaluate, model, and identify processes in info-communication systems. These are [1–3,5]: game theory, fuzzy sets, graph theory, Petri nets, digital automata theory, random process theory, and so on.

These methodologies form a toolkit for analyzing the performance of the studied information systems for a finite censored time. The analysis takes place in the context of determining: 1. The time between failures in the system under study; 2. The number of failures in the study system for the censored period of its operation; 3. The reaction of the studied system to the provoked failures; 4. The reaction of the studied system to complex test effects. In the context of info-communication systems, failures are understood as situations of loss of incoming requests or premature termination of their service.

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Models [6–9] are created with a focus on the description of the first performance indicator. They are based on the mathematical apparatus of time series analysis. Their purpose is to identify the

parameters of the statistical distribution, which best describes the period between failures in the operation of the studied system. The adequacy of such models is determined by the representativeness of the data sample that characterizes the studied system's operation. When formalizing such models, only the fact of failure is taken into account without analyzing the causes of its occurrence and possible consequences.

Models [10–13] were created focusing on the description of the second performance indicator. It is assumed that the stochastic parameter, which characterizes the number of failures in time, is described by a certain distribution law (most often Poisson's) with a continuous or discrete intensity function. The latter is determined by the results of static analysis of operational data. The disadvantages of this type of model are similar to those mentioned above.

Models [14–18] were created focusing on the description of the third performance indicator. The data for analysis in these models are:

- the number of failures in the operation of the studied system for the censored period, which was caused by unknown factors;
- the number of failures in the operation of the studied system during the censored period, which was caused by factors, the mechanisms of counteraction which were embedded in the studied system at the stage of its design.

Data analysis is carried out by combinatorics and maximum likelihood methods. Such models are more informative but still based on information, some of which were collected due to uncontrolled experiments.

Models [19–23] were created focusing on the description of the fourth operational indicator based solely on the results of controlled experiments. Considering that the causes of failures are usually interrelated, models of this type are based on the mathematical apparatus of Markov chains. This allows us to take into account the multithreading in the operation of the studied system and the heterogeneity of the process of its recovery after a failure. Semi-Markov models more accurately describe the behaviour of real information systems because the process of recovery of the first ones after failure can be characterized not only by the exponential distribution function. The structural features of the studied system in this modelling approach can be taken into account in the graph of the control flow, which brings the Markov based model closer to the described process. This qualitatively distinguishes the Markov approach from, for example, a nonparametric neural network, in which the structural features of the studied system are ignored.

Considering the above, we will focus on the Markov approach to the description of the studied ecosystem's operation process [24–27]. Close analogues of the models of operation of info-communication systems based on discrete Markov chains are described in articles [21–23]. These models are based on elements of reliability theory and describe the studied info-communication system as a system with failures and recoveries. In the mentioned studies, the studied system's operation process is formalized in the metrics of absolute qualitative indicators of the theory of reliability. At the same time, the economic aspect is completely ignored. However, the results presented by the authors of these studies have shown that Markov processes can be used to model the response of info-communication systems to input influences if the latter can be considered stochastic and independent. Based on these postulates, the use of Markov processes to model the operation of info-communication systems is permissible [28].

The object of research is the operation process of a centralized wireless information ecosystem focused on multimedia streaming. The aim of the study is the analytical formalization of this process

in the parametric space of qualitative parameters of reliability and economic efficiency.

3. Materials and methods

3.1. Statement of the research

We will study the ecosystem of the cluster of the centralized wireless network of multimedia streaming [29–31]. Let the width of the communication channel of the base transceiver station (BTS) be ν Mbps. Two info-communication streams are sent to the BTS interface.

The first summarizes requests from a set of multiple end-users of multimedia content with a capacity of s . An arbitrary representative of this set with exponentially distributed intensity β_1 sends real-time multimedia transfer requests to the BTS interface. If such a request is made, BTS will spend b_1 Mbps on the resource of the communication channel. This communication channel resource is reserved for the corresponding subscriber for a time equal to the average α_1^{-1} , where α_1 is the parameter of the exponential distribution of the stochastic value of the average duration of the multimedia transfer session. If at the time of receipt of the request for multimedia transfer, the free share of the resource of the communication channel is less than b_1 , the incoming request is not accepted for service and is lost.

The second input stream summarizes requests from an infinite number of end-users of textual information. An arbitrary representative of this set with intensity λ_2 , distributed according to Poisson's law, sends to the BTS interface requests for text data transfer.

If such a request is accepted, BTS will spend b_2 Mbps of the communication channel resource on its support. This communication channel resource is reserved for the corresponding subscriber for a time equal to the average α_2^{-1} , where α_2 is the parameter of the exponential distribution of the stochastic value of the average duration of the text data transfer session. If at the time of receipt of the request for transfer of text data the free share of the resource of the communication channel is less than b_2 , then such a request is not accepted for service and is lost.

Let us summarize by tuple (i_1, i_2) the number of multimedia and text data transfer sessions, respectively, which BTS supports when receiving its input request for text data transfer. Accordingly, at this moment, the share of the resource of the communication channel is equal to $i = b_1 i_1 + b_2 i_2$ what is used. The second stream is by definition, prone to BTS overload. To prevent this, we introduce the self-limiting function $\varphi_2(i)$ in such a way that when performing equations.

$$\varphi_2(\nu + 1 - \theta_1) = 1, \varphi_2(\nu + 2 - \theta_1) = 1, \dots,$$

$$\varphi_2(\nu - 1) = 1, \varphi_2(\nu) = 1 \quad (1)$$

in the BTS information environment for servicing the first stream, the share of the communication channel resource is reserved equal to θ_1 . Until all equations (1) are met, BTS will reject incoming text data transfer requests. It would be rational to consider $\theta_1 \equiv b_1$. The formulated initial provisions are presented in Fig. 1.

3.2. Mathematical model of the studied process

Let the parameters $i_1(t)$ and $i_2(t)$ characterize the number of supported BTS sessions of multimedia and text data transfer at the time t , respectively. The change in the values of these parameters over time is described by a two-dimensional stochastic process $r(t) = \{i_1(t), i_2(t)\}$, which is defined on a finite space of states $\Omega = \{(i_1, i_2)\} \forall i = b_1 i_1 + b_2 i_2 \leq \nu$. According to the initial pro-

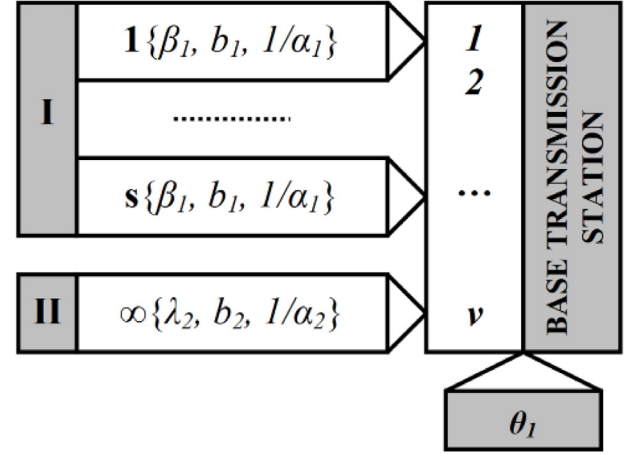


Fig. 1. Starting points of the study.

visions, we distinguish the state's space Ω subspace $S \in \Omega$, which includes states that satisfy the definite condition of self-limitation (1). We also define the state space B_1 , which includes states that characterize the situations of rejection of incoming requests for multimedia transfer due to lack of the required share of free resources of the communication channel: $B_1 = \{(i_1, i_2)\} \forall i = b_1 i_1 + b_2 i_2 \geq \nu + 1 - b_1$. Considering that the stochastic parameters α_1^{-1} and α_2^{-1} are distributed exponentially and independently, we postulate the Markov nature of the process $r(t)$. We describe the probability that BTS supports i_1 sessions for multimedia transfer and i_2 sessions for text data transfer by a parameter $P(i_1, i_2)$. By definition, the parameter $P(i_1, i_2)$ is equal to the ratio of the duration of the process $r(t)$ in state (i_1, i_2) to the total time of observation of the ecosystem.

Based on this definition, we express such qualitative characteristics of the studied process as:

- the percentage of lost requests for multimedia transfer $\pi_{c,1}$;
- the percentage of lost requests for text data transfer $\pi_{c,2}$;
- the average share of BTS communication channel resources involved in multimedia transfer services m_1 ;
- the average share of the BTS communication channel resource involved in the service of text data transfer m_2 . Relevant analytical expressions are given below:

$$\pi_{c,1} = \frac{\sum_{(i_1, i_2) \in B_1} \beta_1 (s - i_1) P(i_1, i_2)}{\beta (s - i_1) P(i_1, i_2)} \quad (2)$$

$$\pi_{c,2} = \sum_{(i_1, i_2) \in S} \varphi_2(i) P(i_1, i_2) \quad (3)$$

$$m_1 = \sum_{(i_1, i_2) \in S} b_1 i_1 P(i_1, i_2) \quad (4)$$

$$m_1 = \sum_{(i_1, i_2) \in S} b_2 i_2 P(i_1, i_2) \quad (5)$$

where c is the number of lost requests.

Next, we express the potential number of multimedia transfer sessions for the first stream of incoming requests from the number of subscribers equal to s :

$$a_1 = \frac{\beta_1 \alpha_1^{-1} s}{1 + \beta_1 \alpha_1^{-1}} \quad (6)$$

We will also determine:

- the percentage of censored operating time of the studied system when the incoming request for multimedia transfer was rejected due to lack of the required share of free resources of the communication channel $\pi_{t,1}$;
- the ratio of the number of lost multimedia transfer requests to the potential number of transfer sessions (6) $\pi_{l,1}$.

Relevant analytical expressions we present below:

$$\pi_{t,1} = \sum_{(i_1, i_2) \in B_1} P(i_1, i_2) \quad (7)$$

$$\pi_{l,1} = a_1^{-1} \left(a_1 - \sum_{(i_1, i_2) \in S} i_1 P(i_1, i_2) \right) \quad (8)$$

Special attention should be paid to characteristic (8) because, by definition, it describes the benefits lost by the studied system.

To evaluate a specific information system in the metrics of characteristics (2)–(5), (7), (8) it is necessary based on data on the results of its operation for a censored time to calculate the probabilities $P(i_1, i_2)$. The latter is possible only in the presence of an appropriate system of statistical equilibrium equations.

Changing the state of (i_1, i_2) the studied ecosystem is possible as a result of 1. Receipt to the BTS interface of the incoming request for multimedia transfer (intensity $\beta_1(s - i_1)$); 2. Receipt to the BTS interface of an incoming request for text data transfer (intensity λ_2); 3. End of support for one of the multimedia transfer sessions (intensity $\alpha_1 i_1$); 4. End of support for one of the text data transfer sessions (intensity $\alpha_2 i_2$). Let's explore each of these events.

The occurrence of event 1 changes the current state of the ecosystem (i_1, i_2) to a state $(i_1 + 1, i_2)$ with intensity $P(i_1, i_2)\beta_1(s - i_1)$ with a probability equal to one if there is a corresponding share of free resources of the communication channel ($i \leq v - b_1$).

The occurrence of event 2 changes the current state of the ecosystem (i_1, i_2) to the state $(i_1, i_2 + 1)$ with intensity $P(i_1, i_2)\lambda_2(1 - \varphi_2(i))$ with a probability equal to $1 - \varphi_2(i)$, if the existing condition of self-limitation (1), expressed taking into account the function $\varphi_2(i)$, is fulfilled.

The occurrence of event 3 changes the current state of the ecosystem (i_1, i_2) to the state $(i_1 - 1, i_2)$ with intensity $P(i_1, i_2)\alpha_1 i_1$ with a probability equal to one, if the termination condition for the active multimedia transfer session is met.

The occurrence of event 4 changes the current state of the ecosystem (i_1, i_2) to a state $(i_1, i_2 - 1)$ with intensity $P(i_1, i_2)\alpha_2 i_2$ with a probability equal to one of the termination conditions for the active session of text data transfer is met.

Analytical results of the analysis of events 1–4 allow us to implement the left parts of the corresponding equations of the statistical equilibrium system. To obtain the right parts, it is necessary to describe events 1–4 in the context of the transition of the process $r(t)$ from an arbitrary state to a state (i_1, i_2) .

The occurrence of event 1 changes the current state of the ecosystem $(i_1 - 1, i_2)$ to a state (i_1, i_2) with intensity $s + 1 - i_1$ if the condition $(i_1 - 1, i_2) \in S$ is fulfilled.

The occurrence of event 2 changes the current state of the ecosystem $(i_1, i_2 - 1)$ to a state (i_1, i_2) with intensity $1 - \varphi_2(i - b_2)$ if the condition $(i_1, i_2 - 1) \in S$ is fulfilled.

The occurrence of event 3 changes the current state of the ecosystem $(i_1 + 1, i_2)$ to the state (i_1, i_2) with intensity $P(i_1 + 1, i_2)\alpha_1(i_1 + 1)$ if the condition $(i_1 + 1, i_2) \in S$ is fulfilled.

The occurrence of event 4 changes the current state of the ecosystem $(i_1, i_2 + 1)$ to the state (i_1, i_2) with intensity $i_2 + 1$ if the condition $(i_1, i_2 + 1) \in S$ is fulfilled.

Summarize the results in the form of a system of statistical equilibrium equations:

$$\begin{aligned} P(i_1, i_2)(\beta_1(s - i_1)I(i \leq v - b_1) + \lambda_2(1 - \varphi_2(i)) + \\ + \alpha_1 i_1 I(i_1 > 0) + \alpha_2 i_2 I(i_2 > 0)) = \\ = P(i_1 - 1, i_2)\beta_1(s + 1 - i_1)I(i_1 > 0) + \\ + P(i_1, i_2 - 1)\lambda_2(1 - \varphi_2(i - b_2))I(i_2 > 0) + \\ + P(i_1 + 1, i_2)\alpha_1(i_1 + 1)I(i + b_1 \leq v) + \\ + P(i_1, i_2 + 1)\alpha_2(i_2 + 1)I(i + b_2 \leq v), \end{aligned} \quad (9)$$

where $I(\dots)$ is an indicator function equal to 1, if the condition in its argument is met, or 0 - otherwise.

The solution of system (9) satisfies the rationing condition:

$$\sum_{(i_1, i_2) \in S} P(i_1, i_2) = 1$$

When describing real processes of type $r(t)$, the number of linear equations in the system (9) can reach thousands. This circumstance necessitates a more detailed consideration of the process of solving the system of statistical equilibrium equations (9).

Considering the potential dimension of the system of equations (9), it is not practical to apply classical methods for sequential exclusion of unknown or block transformations to solve it. According to the authors, the iterative modification of the method of sequential substitution, in particular, the iterative Gauss-Seidel method, looks more promising [32]. The advantage of this method is that it is not necessary to memorize the matrix (9). It is enough to calculate its coefficients at each iteration of the algorithm. We adapt the mentioned algorithm for our case.

We maintain the parameter $P^{(k)}(i_1, i_2), (i_1, i_2) \in S$, which will store the value of the k -th approximation as a result of the implementation of the corresponding iteration of the Gauss-Seidel algorithm. The $k + 1$ -th approximation is obtained based on the k -th approximation as a result of a recursive procedure of type.

$$\begin{aligned} P^{(k+1)}(i_1, i_2) = & \left(P^{(k+1,k)}(i_1 - 1, i_2)\beta_1(s + 1 - i_1) \times \right. \\ & \times I(i_1 > 0) + P^{(k+1,k)}(i_1, i_2 - 1)\lambda_2(1 - \varphi_2(i - b_2)) \times \\ & \times I(i_2 > 0) + P^{(k+1,k)}(i_1 + 1, i_2)\alpha_1(i_1 + 1)I(i + b_1 \leq v) + \\ & \left. + P^{(k+1,k)}(i_1, i_2 + 1)\alpha_2(i_2 + 1)I(i + b_2 \leq v) \right) \times \\ & \times (\beta_1(s - i_1)I(i \leq v - b_1) + \lambda_2(1 - \varphi_2(i)) + \\ & + \alpha_1 i_1 I(i_1 > 0) + \alpha_2 i_2 I(i_2 > 0))^{-1}, \end{aligned} \quad (10)$$

where $P^{(k+1,k)}(i_1, i_2)$ means: if the $k + 1$ -th approximation is unknown, then the k -th approximation is used for calculation.

Initiation of the iterative calculation procedure, generalized by expression (10), requires setting the starting point and the criterion for completing the calculation. We define the first of these components as $P^{(0)}(i_1, i_2) = 1, (i_1, i_2) \in S$, and the second as.

$$\frac{\sum_{(i_1, i_2) \in S} |P^{(k+1)}(i_1, i_2) - P^{(k)}(i_1, i_2)|}{\sum_{(i_1, i_2) \in S} P^{(k)}(i_1, i_2)} < \delta$$

where the value of the constant δ is selected from the range $[10^{-10}, 10^{-8}]$.

4. Simulation and results

Let's apply the mathematical apparatus presented in Section 3 to simulate the ecosystem of the cluster of the centralized wireless network of multimedia streaming based on equipment certified for the 4G generation.

The studied ecosystem is designed to support up to 20 sessions of multimedia transfer and up to 1000 sessions of text data trans-

fer. To maintain a session of the first or second type, a share of the communication channel resource equal to $b_1 = 5$ or $b_2 = 1$, respectively, is spent. At the same time, the subscription base of users who have privileges for the multimedia transfer includes $s = 100$ people.

Determine the dependence of the values of quality indicators (2) and (3) on the value of traffic intensively indicator for the studied ecosystem: $\{\pi_{c,1}, \pi_{c,2}\} = f(\rho)$. The load indicator ρ is defined as $\rho(i) = v^{-1}(b_1 a_1(i) + b_2 a_2(i))$. In turn, the parameters $a_1(i)$ and $a_2(i)$ were determined by the expressions $a_1(i) = b_1^{-1} a_2(i)$ and $a_2(i) = 2,5i$, where $i = 1, 400$. The established parameters of the model were developed as follows: $v = 10^3$, $\alpha_1 = \alpha_2 = 1$, $\beta_1 = (s - a_1)^{-1} a_1$, $\lambda_2 = a_2$, $a_1 \in [0, 20]$, $a_2 \in [0, 1000]$.

The calculated dependences d are presented in Fig. 2.

Emphasizing that the qualitative indicators (2) and (3) are stochastic and relative. To obtain a holistic view of the development of the studied process $r(t)$, it is necessary to calculate the dependencies $\{m_1, m_2\} = f(\rho)$ under the same conditions of the experiment under which the results presented in Fig. 2 were obtained. Absolute qualitative parameters m_1 and m_2 are calculated by expressions (4) and (5), respectively. Note that at the initial stage of this experiment, the resource of the communication channel is symmetrically divided between the traffic of multimedia transfer and text data transfer (for $\rho = 0, 1$ both curves comes from one point of the y-axis).

The results of this experiment are presented in Fig. 3.

The experience of the actual operation of the studied ecosystem shows that as the ratio of b_1/b_2 increases, the share of lost requests for text data transfer increases, but at the same time the tendency to displace multimedia transfer traffic with text data transfer traffic increases. Let us investigate whether the mathematical apparatus presented in Section 3 reproduces the trends described. To do this, calculate the dependences of $\pi_{c,1} = f(\rho; b_1 = \{50, 25, 10, 5\})$ for $s = 250$. Other established parameters, $b_2 = 1$, did not change relative to previous experiments.

The obtained results are presented in Fig. 4.

Again, based on the results of the operation of the real ecosystem, it can be argued that preventing the transfer of multimedia transfer traffic by text data transfer traffic is possible only by reserving a share of the communication channel resource for the stream of the first type. In the mathematical apparatus presented in Section 3, this possibility is described by the self-limiting

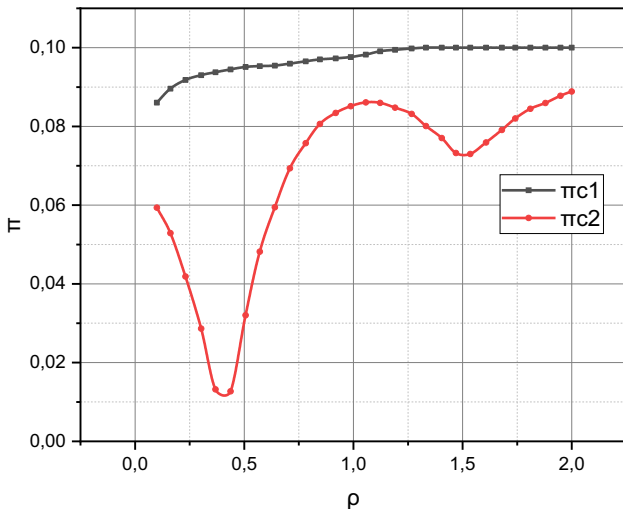


Fig. 2. Simulation results: dependencies $\{\pi_{c,1}, \pi_{c,2}\} = f(\rho)$.

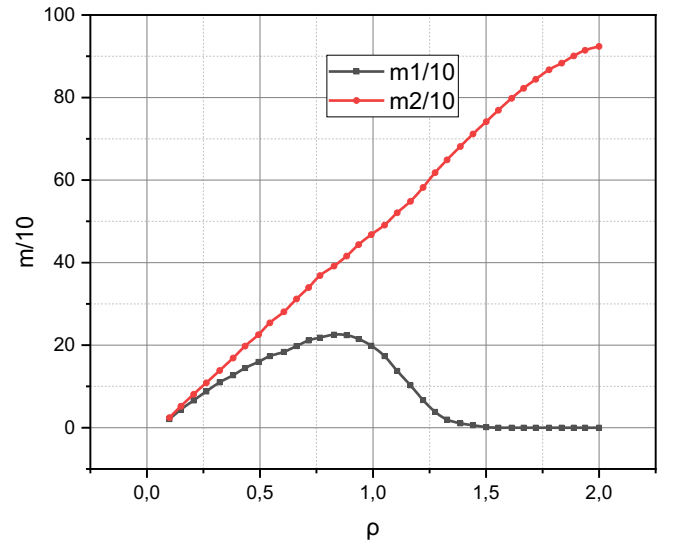


Fig. 3. Simulation results: dependencies $\{m_1, m_2\} = f(\rho)$.

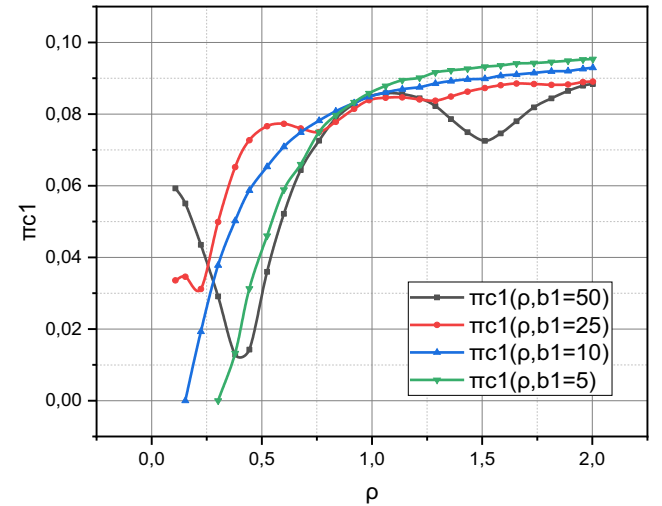


Fig. 4. Simulation results: dependencies $\pi_{c,1} = f(\rho; b_1 = \{50, 25, 10, 5\})$.

function $\varphi_2(i)$, the value of which for the corresponding value of the argument is selected so that when performing equalities (1) a share of the resource of the communication channel is equal to θ_1 for media traffic was reserved.

Let us investigate the effect of the introduction of the self-limitation function $\varphi_2(i)$. To do this, we calculate the dependencies $\{\pi_{c,1}, \pi_{c,1}^{\varphi}, \pi_{c,2}, \pi_{c,2}^{\varphi}\} = f(\rho)$ where the parameter $\pi_{c,j}^{\varphi}$, $j = \{1, 2\}$, characterizes the percentage of lost requests for the transfer of multimedia or text data in an ecosystem with an active self-limiting function. The experiment was performed under conditions similar to those that allowed obtaining the results presented in Figs. 2 and 3. The only difference is $b_1 = 50$, for which the value of θ_1 was determined: $\theta_1 = b_1$.

The results of the study are summarized in Fig. 5.

Considering that the process of operating a multimedia streaming ecosystem is commercial, an important aspect is to establish the fact that it is effective in using the resource of the communication channel. It should be borne in mind that without activating the self-limiting function, the communication channel will eventually be loaded by the stream of the second type, which is not a

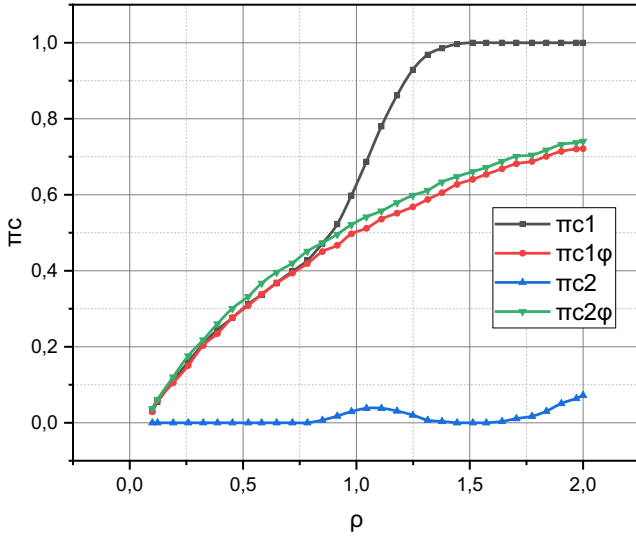


Fig. 5. Simulation results: dependencies $\{\pi_{c,1}, \pi_{c,1}^\phi, \pi_{c,2}, \pi_{c,2}^\phi\} = f(\rho)$.

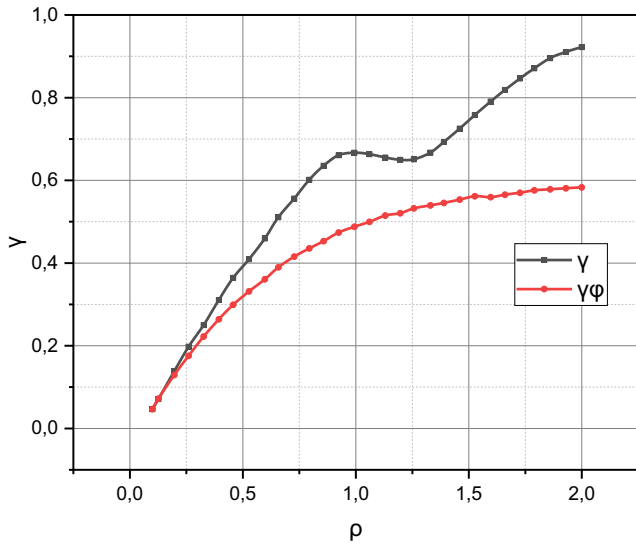


Fig. 6. Simulation results: dependencies $\{\gamma, \gamma^\phi\} = f(\rho)$.

priority for the studied ecosystem. At the same time, activating the self-limiting feature can potentially cause the communication channel to be underloaded due to the rejection of text data transfer requests.

So, let's connect the concept of efficiency of use of the communication channel resource by the studied ecosystem with the parameter $\gamma = v^{-1}(m_1 + m_2)$. The experiment will be based on the calculation of the dependencies $\{\gamma, \gamma^\phi\} = f(\rho)$, which γ^ϕ is an indicator of the efficiency of the use of the communication channel resource by an ecosystem with an activated self-limiting function. The experiment was performed under conditions similar to the previous one.

The obtained results are visualized in Fig. 6.

5. Discussion

Let's start the analysis of the results of experiments from the description in Figs. 2 and 3. These figures show the behaviour of

the studied ecosystem focused on multimedia streaming in the parametric space of parameters (2)–(5), namely:

- the percentage of lost requests for multimedia transfer $\pi_{c,1}$;
- the percentage of lost requests for text data transfer $\pi_{c,2}$;
- the average share of the resource of the BTS communication channel involved in the service of multimedia transfers m_1 ;
- the average share of the BTS communication channel involved in the service of text data transfers m_2 .

Fig. 2 shows that from the initial value of the ecosystem load $\rho = 0,1$ and further for all values of this parameter, the tendency to displace multimedia transfer traffic with text data transfer traffic is maintained and intensified.

The different nature of the functions $\pi_{c,1} = f(\rho)$ $\pi_{c,2} = f(\rho)$ is due to the consideration proposed in Section 3 of the fact that different distribution laws describe the characteristic parameters of these flows. The example of the dependence $\pi_{c,2} = f(\rho)$ shows that the process of the dominance of text data transfer traffic increases abruptly. While it is possible to increase the volume of text data transfer traffic due to multimedia transfer traffic, the probability of losing the requests of the second type decreases. Under the conditions of the experiment, $b_1/b_2 = 5$ the BTS initiates five text data transfer sessions at the end of one multimedia transfer session. But with increasing ρ , the share of multimedia transfer sessions in the BTS communication channel decreases exponentially, so the amplitude of the oscillation of the dependence $\pi_{c,2} = f(\rho)$ decreases.

The same tendencies, but in absolute units of values of parameters m_1 and m_2 we can see in Fig. 4. The experiment begins when the BTS channel resource is split in half between the first and second type streams of incoming requests (one starting point for both $m_1 = f(\rho)$ and $m_2 = f(\rho)$ dependencies). As the congestion value ρ increases, the average share of the BTS channel resource used in the multimedia transfer service m_1 increases more slowly with the value of the parameter m_2 . Further growth occurs by decreasing the value $\rho \approx 0,8$ until the entire resource of the communication channel is flooded with text data traffic ($\rho \approx 1,9$ and so on).

We have already linked the nature of the oscillation of the dependence $\pi_{c,2} = f(\rho)$ with the value of the dependence b_1/b_2 . Considering that the purpose of the studied ecosystem is the transfer of multimedia, it is impossible to ignore the influence of the value b_1/b_2 on the behaviour of the parameter $\pi_{c,1}$ in conditions of increasing the value of the load indicator ρ . This information is presented in Fig. 4. We can see that the dependencies $\pi_{c,1} = f(\rho; b_1 = 10)$ and $\pi_{c,1} = f(\rho; b_1 = 10)$ are devoid of oscillations, in contrast to other dependencies (for $b_1 = \{50, 25\}$). It is also seen that $b_1 = \{10, 5\}$ the displacement of multimedia transfer traffic does not start immediately, but at $\rho = \{0, 2; 0, 3\}$. Moreover, with decreasing value of b_1/b_2 this trend increases, which indicates favour of the adequacy of the proposed mathematical apparatus.

In general, presented in Figs. 2–4, results convincingly prove that the studied ecosystem cannot fulfil its purpose at a moderate and high load without introducing the self-limiting function. Fig. 5 shows that introducing the self-limiting function of the form (1) $\theta_1 = b_1$ gives an unambiguously positive effect. If the dependencies $\{\pi_{c,1}, \pi_{c,2}\} = f(\rho)$ (self-limitation is deactivated) show the usual displacement of multimedia transfer traffic by text data traffic, then with active self-limitation ($\{\pi_{c,1}^\phi, \pi_{c,2}^\phi\} = f(\rho)$) the loss of incoming requests does not depend on their type but is due to increasing the value of the load indicator ρ .

Finally, interpret the presented in Fig. 6 results are simple: the smaller the dynamics of growth of an arbitrary dependence of the form $\gamma = f(\rho)$, the more efficiently the resource of the communication channel is used. This criterion shows that the introduction of

the self-limiting function of the form (1) $\theta_1 = b_1$ allows not only to ensure that the studied ecosystem fulfils its purpose at any load on the communication channel but also to do it almost twice as efficiently. However, the growing dynamics of the dependence $\gamma^\varphi = f(\rho)$ indicate that the choice $\theta_1 = b_1$ is suboptimal. This circumstance allows us to consider promising to direct further research toward setting and solving the task of finding the optimal type and values of controlled variables of the self-restraint function $\theta_1 = b_1$.

6. Conclusion

The basis of the digital society is the ability to effectively communicate with communities, people and things. It should be borne in mind that people are natural and comfortable communicating in video conferencing, while IoT devices mostly exchange text messages. As the size of these user audiences in today's cyberspace grows exponentially, communication tools and their information systems become bottlenecks in the path of progress. Thus, the study of the functioning of a centralized wireless information ecosystem (as a basic link of modern info-communication infrastructure), focused on multimedia streaming, is relevant.

The highlights of the article are the Markov model of functioning of the centralized wireless information ecosystem focused on multimedia streaming. The model describes the stochastic process of joint service by the BTS of independent streams of multimedia transfer and text data transfer. To assess the effectiveness of the fulfilment of its purpose by the studied ecosystem a metric of quality parameters is proposed, in particular:

- the percentage of lost requests for multimedia transfer;
- the percentage of lost requests for text data transfer; - the average share of the resource of the BTS communication channel involved in the service of multimedia transfers;
- the average share of the BTS communication channel involved in the service of text data transfer;
- the percentage of censored operating time of the studied system, when the incoming request for multimedia transfer was rejected due to lack of the required share of free resources of the communication channel;
- the ratio of the number of lost multimedia transfer requests to the potential number of transfer sessions.

The first four parameters are indicators of the reliability of the studied system, and the last two qualitative parameters have a direct economic interpretation. For the studied ecosystem to be able to realize its purpose in conditions of moderate and high load, the model introduced a self-limiting function. This feature allows us to flexibly balance the process of servicing transfer sessions of both types, balancing the values of the first two quality indicators. The adequacy of the proposed mathematical apparatus is proved empirically.

Analysis of the real ecosystem with the help of the created mathematical apparatus has shown that the function of self-restraint is a means of controlling the efficiency of use of the resource of the communication channel. This circumstance allows us to consider promising to direct **further research** toward setting and solving the task of finding the optimal type and values of controlled variables of this function. We also note that the scientific and applied results presented in the article were tested in the 4G ecosystem. At the same time, the authors suggest that the theoretical results obtained can be adapted to describe the competing interaction of enhanced Mobile BroadBand (eMBB) and massive Machine-Type Communication (mMTC) services in the 5G ecosystem. The authors are going to confirm or refute this thesis in further studies.

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CRediT authorship contribution statement

Viacheslav Kovtun: Writing – review & editing. **Ivan Izonin:** Writing – review & editing. **Michal Gregus:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Sampaio N A de S et al. Contributions to the future of metaheuristics in the contours of scientific development. *Gestão & Produção* 2022;29. doi: <https://doi.org/10.1590/1806-9649-2022v29e099>.
- [2] Kovács Á, Gódor I. Cross-layer optimized wireless multicast for layered media. *Comput Netw* 2009;53(7):1062–72.
- [3] Kiss M, Breda G, Muha L. Information security aspects of Industry 4.0. *Proc Manuf* 2019;32:848–55. doi: <https://doi.org/10.1016/j.promfg.2019.02.293>. Elsevier BV.
- [4] Panchenko S, Trubchaninova K, Korago I. Minimization method for average packet delay in data transmission networks. *Proc Computer Sci* 2019;149:177–84. doi: <https://doi.org/10.1016/j.procs.2019.01.121>. Elsevier BV.
- [5] Anagnostopoulos T, Kolomvatsos K, Anagnostopoulos C, Zaslavsky A, Hadjiefthymiades S. Assessing dynamic models for high priority waste collection in smart cities. *J Syst Softw* 2015;110:178–92.
- [6] Kuznetsov NA, Myasnikov DV, Semnikhin KV. Two-phase queueing system optimization in applications to data transmission control. *Proc Eng* 2017;201:567–77.
- [7] Gál Z, Kocsis G, Tajti T, Tornai R. Performance evaluation of massively parallel and high speed connectionless vs. connection oriented communication sessions. *Adv Eng Software* 2021;157–158:103010. doi: <https://doi.org/10.1016/j.advengsoft.2021.103010>. Elsevier BV.
- [8] Pantano M, Regulin D, Lutz B, Lee D. A human-cyber-physical system approach to lean automation using an industrie 4.0 reference architecture. *Procedia Manuf* 2020;51:1082–90.
- [9] Scholliers J, Jutila M, Valtä M, Kauvo K, Virtanen A, Pyykönen P. Co-operative traffic solutions for hybrid communication environments. *Transp Res Procedia* 2016;14:4542–51.
- [10] Shin D-H. User centric cloud service model in public sectors: Policy implications of cloud services. *Govern Inform Quart* 2013;30(2):194–203.
- [11] Siddhpura AVI, Siddhpura M. Current state of research in application of disruptive technologies in engineering education. *Proc Computer Sci* 2020;Vol. 172:494–501. doi: <https://doi.org/10.1016/j.procs.2020.05.163>. Elsevier BV.
- [12] Bolodurina I, Parfenov D. Comprehensive approach for optimization traffic routing and using network resources in a virtual data center. *Proc Computer Sci* 2018;136:62–71. doi: <https://doi.org/10.1016/j.procs.2018.08.238>. Elsevier BV.
- [13] Krzywicki K, Andrzejewski G, Zajac W, Krolikowski T, Barkalov A, Titarenko L. IPNES – interpreted petri net for embedded systems. *Proc Comput Sci* 2021;192:2012–21. Elsevier BV.
- [14] Verma S, Ghazel M, Berbinau M. Model-based dependability evaluation of a wireless communication system in a virtually coupled train set. *IFAC-PapersOnLine* 2021;54(2):179–86. Elsevier BV.
- [15] Igbinosa OG, Okpeki UK. Performance investigation of different pathloss models for a wireless communication system in Nigeria. *Heliyon* 2019;5(5):e01656. Elsevier BV.
- [16] Sharma V, Kumar N. Modeling of 2.5 Gbps-intersatellite link (ISL) in inter-satellite optical wireless communication (IsOWC) system. *Optik* 2013;124(23):6182–5. Elsevier BV.
- [17] Savkin AV, Matveev AS, Rapajic PB. The medium access control problem for wireless communication networks modelled as hybrid dynamical systems. *Nonlinear Anal Theory Methods Appl* 2005;62(8):1384–93. Elsevier BV.
- [18] Gummineni M, Polipalli TR. Implementation of reconfigurable emergency wireless communication system through SDR relay. *Mater Today Proc* 2021. doi: <https://doi.org/10.1016/j.matpr.2021.03.352>. Elsevier BV.
- [19] Kalnoor G, Subrahmanyam G. A review on applications of markov decision process model and energy efficiency in wireless sensor networks. *Procedia Comput Sci* 2020;167:2308–17.

- [20] Su X, Li Y, Gao M, Wang Z, Li Y, Zhu Y. Online policies for throughput maximization of backscatter assisted wireless powered communication via reinforcement learning approaches. *Pervasive Mobile Comput* 2021;77:101463. doi: <https://doi.org/10.1016/j.pmcj.2021.101463>. Elsevier BV.
- [21] Guo Q, Xu Q. The economic benefits of agglomeration of the internet of things industry based on 5 g network and markov chain. *Microprocessors Microsystems* 2020;103438. doi: <https://doi.org/10.1016/j.micpro.2020.103438>. Elsevier BV.
- [22] Küçük K, Msongaleli DL, Akbulut O, Kavak A, Bayılmış C. Self-adaptive medium access control protocol for aggregated VLC–RF wireless networks. *Opt Commun* 2021;488:126837. Elsevier BV.
- [23] Liao X, Wu Z, Zhang Y, Jiang X. Buffer-aided relay selection for secure communication in two-hop wireless networks with limited packet lifetime. *Ad Hoc Netw* 2021;121:102580. doi: <https://doi.org/10.1016/j.adhoc.2021.102580>. Elsevier BV.
- [24] Dalkani H, Mojarad M, Arfaeinia H. Modelling electricity consumption forecasting using the markov process and hybrid features selection. *Internat J Intell Syst Appl (IJISA)* 2021;13(5):14–23. doi: <https://doi.org/10.5815/ijisa.2021.05.02>.
- [25] Burkhardt J. Bayesian parameter inference of explosive yields using markov chain monte carlo techniques. *Internat J Math Sci Comput (IJMSC)* 2020;6(2):1–17. doi: <https://doi.org/10.5815/ijmsc.2020.02.01>.
- [26] Hitigala PK, Kaluarachchilage CA, Rajasooriya S, Tsokos CP. An analytical approach to assess and compare the vulnerability risk of operating systems. *Internat J Comput Network Inform Secur (IJCNIS)* 2020;12(2):1–10. doi: <https://doi.org/10.5815/ijcnis.2020.02.01>.
- [27] G Savakar D, Kannur A, Kannur Anil. Hidden Markov model for identification of different marks on human body in forensic perspective. *Internat J Modern Educ Comput Sci (IJMECS)* 2019;11(3):38–45.
- [28] Ezichi S, Ezika IJF, Iloanusi ON. A comparative study of soft biometric traits and fusion systems for face-based person recognition. *Internat J Image Graph Signal Process (IJIGSP)* 2021;13(6):45–53. doi: <https://doi.org/10.5815/ijigsp.2021.06.05>.
- [29] Ali S, Pandey M, Tyagi N. SDFog-Mesh: A software-defined fog computing architecture over wireless mesh networks for semi-permanent smart environments. *Comput Netw* 2022;211:. doi: <https://doi.org/10.1016/j.comnet.2022.108985>108985.
- [30] Bai Z, Yang L, Fu C, Liu Z, He Z, Zhu N. A robust approach to integrated wireless charging infrastructure design and bus fleet size optimization. *Comput Ind Eng* 2022;168:. doi: <https://doi.org/10.1016/j.cie.2022.108046>108046.
- [31] Alwesabi Y, Avishan F, Yanikoğlu İ, Liu Z, Wang Y. Robust strategic planning of dynamic wireless charging infrastructure for electric buses. *Appl Energy* 2022;307:. doi: <https://doi.org/10.1016/j.apenergy.2021.118243>118243.
- [32] Falade KI, Tiarniyu AT. Numerical solution of partial differential equations with fractional variable coefficients using new iterative method (NIM). *Internat J Math Sci Comput (IJMSC)* 2020;6(3):12–21.