

COMPREHENSIVE METHOD OF ENERGY-EFFICIENT WORKLOAD PROCESSING IN THE INFORMATION AND COMMUNICATION NETWORK

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Background. Peculiarities of the workload in a modern information and communication network (ICN) determine specific requirements for energy efficiency, performance and availability of its processing system. Existing approaches to increase energy efficiency and performance of workload processing do not take into account the possibility of dynamic changes in ICN workload arrival rate and individual energy consumption characteristics of computing nodes of the system.

Objective. The purpose of the paper is to increase the energy efficiency and performance of ICN workload processing while meeting the requirements for the availability of the processing system, taking into account dynamic changes in the input workload arrival rate and the individual characteristics of the computing nodes' energy consumption.

Methods. A mathematical model of the workload processing system was built using the queueing theory methods, and an ontological model of this system was built using intelligent data analysis methods, which made it possible to quantitatively and qualitatively describe the complex relationships between system parameters and workload processing efficiency indicators. On the basis of the built models, a comprehensive method of energy-efficient workload processing was proposed, which differs from the known ones by the use of individual energy consumption models of computing nodes, combining the advantages of horizontal scaling and energy-efficient scheduling taking into account dynamic changes in workload arrival rate.

Results. The efficiency of ICN workload processing is increased by 15.722% according to the efficiency criterion, which includes energy efficiency and performance indicators, compared to the known energy-efficient Backfill approach while meeting the requirements for the availability of the processing system.

Conclusions. The energy efficiency, performance and availability of the ICN workload processing system can be improved by combining horizontal scaling and energy-efficient scheduling approaches using individual energy consumption models of computing nodes and taking into account dynamic changes in the input workload arrival rate.

Keywords: *energy efficiency; performance; availability; workload; ICN.*

Introduction

Nowadays, the concept of "telecommunication network" as a complex of technical means of telecommunications and facilities designed for routing, switching, transmission and/or reception of signs, signals or messages of any kind [1] is gradually being replaced by the concept of "information and communication network" (ICN), that is, a network in which a part of the functions of technical telecommunication means is replaced by software due to the property of the so-called network programmability [2]. Programmability is provided by a number of technologies that allow transferring the network tasks (for example, routing, switching, network address translation, management and reconfiguration of network resources, network traffic analysis, etc.) from specialized hardware (router, switch, etc.) to general-purpose hardware with specialized software. This ap-

proach makes the network more flexible, simplifies and lowers the costs for its configuration.

Among the technologies and concepts implementing the network programmability paradigm, in particular, the concept of Software-Defined Networking (SDN) [3], Network Functions Virtualization (NFV) [4], Network Slicing [5], Edge Computing [6] and Big data driven networking bDDN [7]. Software developed within these concepts runs on general-purpose servers as part of the ICN computing infrastructure, which is an integral part of a modern network. The tasks solved within these concepts are physically represented by computational jobs and form the workload of the ICN. Moreover, the processing of this workload is subject to requirements determined by the specifics of the performed network tasks. Let us analyse in more detail the service requirements for different types of computer workload.

According to the European Telecommunications Standards Institute specification ETSI GR NFV 003 [4] NFV or network function virtualization is the principle of separating network functions from the hardware on which they run using virtual hardware abstraction. The main idea of NFV is to replace specialized network equipment (e.g., L2 switches, routers, network address translation devices, etc.) with virtualized network functions. SDN or software-configured networks, according to the recommendations of the International Telecommunication Union ITU-T Y.3300 [3], is an approach to the design, implementation and management of ICN, which separates the network management (control plane) and the traffic management process (data plane). This separation greatly simplifies network administration and management. SDN and NFV workload processing requirements are regulated by the International Telecommunication Union in documents ITU-T L.1360 [8] and ITU-T L.1361 [9]. These recommendations indicate the need for comprehensive consideration of requirements for quality of service (QoS) [10], energy efficiency, reliability and safety.

Another key concept is the logical division of the network called Network Slicing - this is the technology of dividing the network into logical levels on top of a single physical infrastructure while simultaneously meeting the needs of various services [11]. According to the recommendations of the International Telecommunication Union ITU-T Y.3156 [12], the concept of network slicing involves the use of artificial intelligence technologies to solve the problems of recognizing and optimizing patterns of logical network levels, predicting traffic, optimizing resources for each logical level, analysing reasons and localization of errors and emergency situations. According to the recommendations of ITU-T Y.3156 [12], ITU T Y.3111 [13], b-ITU-T Y.2701 [14] and ETSI TR 132 972 [15], Network Slicing workload processing should be carried out in compliance with the requirements regarding the provision of QoS for services on individual network levels, provision of real-time service quality analysis data, energy efficiency, data processing security.

The leading place in modern ICNs is occupied by the concept of Edge Computing [6], which implies the transfer of ICN workload processing resources as close as possible to the user in order to increase data processing throughput and reduce latency. According to the recommendations of the International Telecommunication Union ITU-T F.743.12 [16] and ITU-T F.743.10 [17], the ICN tasks that should be solved with the help of a peripheral server infrastructure include, in particular, the tasks of video analysis in video surveillance systems (pre-processing of video surveillance da-

ta, detection and analysis of out-of-state situations, urban traffic analysis, face recognition, etc.), local content caching, tasks of three-dimensional computer simulation for virtual and augmented reality applications. The requirements for servicing the workload within the framework of Edge Computing are mostly determined by the specifics of the tasks being solved and include, in particular, the requirements for providing a response to a request in real time (for example, for the tasks of detecting out-of-state situations using video surveillance systems), simultaneous servicing of a large number of subscriber devices, guaranteed system availability not lower than the level determined by the service level agreement (SLA).

International Telecommunication Union Recommendation ITU-T Y.3652 [18] defines the concept of a bDDN Big Data-driven network as a group of technologies and methods to facilitate the administration, maintenance and optimization of the network based on the Big Data accumulated by the network. The tasks solved within the bDDN concept are the collection and analysis of data on the current network configuration, the state of network equipment, network traffic statistics, the history of errors and failures in the network, the number of subscribers served by base stations, etc. In addition to functional requirements, bDDN workload processing also has performance and security requirements: collection and analysis of network state data must occur in real time; lossless data storage must be ensured; time for data analysis is limited from above by the maximum allowable response time; when serving the bDDN workload, security methods such as authentication, authorization and access control described in ITU-T Y.2704 [19] should be applied.

As we may see, the key requirements for the processing of all considered types of ICN workload include ensuring the QoS requirements, compliance with the maximum permissible response time, the ability to work in real time, the availability of the workload processing system, energy efficiency, reliability and safety of workload processing. At the same time, the QoS indicators (in particular in the 5G network) according to the sources [2, 20] can include: peak data transfer rate for the uplink/downlink communication line, data transfer rate for the end user, "end-to-end" data transfer latency, the packet errors frequency, the efficiency of using the frequency spectrum, the number of connected devices, mobility (the ability to provide communication for moving objects at the speed of movement v). Fulfilling the requirements for QoS indicators, acceptable response time and the ability to work in real time directly depends on the performance of the computing infrastructure that processes the mentioned types of comput-

er workload. Availability and energy efficiency when processing the workload are determined by the availability and energy efficiency of the computing infrastructure, respectively.

At the same time, the problem of ensuring the energy efficiency of workload processing is becoming more and more urgent, since the functioning of a territorially distributed computing infrastructure is very energy-consuming. Thus, according to research data [21, 22], the share of electricity consumption by such systems as of 2020 was about 1% of all electricity produced in the world, and this share of energy consumption continues to grow rapidly, which is due to the rapid increase in the capacities of ICN computing equipment.

Thus, the problem of increasing energy efficiency, performance, availability, reliability and security of computing infrastructure as part of ICN in order to ensure the fulfillment of requirements for ICN workload processing is very important nowadays. Ensuring reliability is a separate aspect studied using the methods of reliability theory [23]. The security of the workload processing is ensured by the implementation of additional approaches to increase the security of data processing. Therefore, the reliability and safety requirements of workload processing are not considered in detail in this study and are a matter for further research. Instead, the article proposes a comprehensive method of energy-efficient processing of ICN workload, which allows simultaneously increasing service performance while complying with the requirements regarding the processing system availability.

State of the art approaches to increase the energy efficiency of ICN workload processing

The problem of increasing energy efficiency, performance and availability of distributed workload processing has been studied in the world for more than a decade. At the same time, the existing studies mostly approach the solution of the problem as finding a trade-off between energy efficiency, performance and availability of the workload processing system based on the assumption that the improvement of energy efficiency clearly affects the indicators of performance and availability negatively. The issue of the interrelationship of these indicators is separately analysed in this paper.

The document of the International Telecommunication Union ITU-T L.1300 [24], along with recommendations for the construction of data centers, contains recommendations for:

- Selection of energy-efficient computing and telecommunications equipment of the data center;
- Energy-efficient deployment of information and communication services;

- Energy-efficient management of telecommunications equipment, services and data.

According to these recommendations, the general approaches to increase the energy efficiency of ICN workload processing are:

- Selection of energy-efficient computer and telecommunication equipment and its regular attestation (audit);
- Deployment of services using virtualization approaches;
- Development of effective software;
- Decommissioning services that are not used and turning off equipment in case of downtime;
- Consolidation of current services;
- Continuous monitoring of system energy consumption.

That is, according to [24], an integrated system approach that takes into account all aspects of energy efficiency, from hardware characteristics to features of software implementation and deployment, is important.

Modern studies of the energy efficiency of workload processing problem are carried out in the following directions:

– *Energy-proportional computing* is a modern concept proposed by Google, which reflects the main goal of energy-efficient computing: reducing the resources' idling time [25].

– *Energy-efficient workload scheduling* – the concept of distributing tasks between computing nodes in such a way that the total energy consumption of all system nodes is minimized.

– *Horizontal scaling* – the main idea of this concept is to temporarily remove from the system (disable) computing nodes that are not involved in processing.

– *Workload consolidation* – this concept is closely related to horizontal scaling, as it aims to consolidate the workload in the system in such a way as to free up some nodes in order to temporarily take them out of the system.

Energy-proportional computing is a general concept that defines the goals and limitations of methods for improving the energy efficiency of a single computing node and distributed computing systems [25]. Within the framework of the concept, special attention is paid to the fact that a large part of the electricity is wasted when the computing nodes are idle, therefore the idea of reducing the computing equipment's idling is promoted as an effective way to increase the energy efficiency of the workload processing.

The basic idea of energy-efficient workload scheduling is to match the available computing resources and the workload. One of the most common energy-efficient workload scheduling strategies is the Backfill

strategy [26]. The basic version of this strategy was proposed by IBM and became the basis for the development of numerous modifications and improvements [27-28]. Backfill is a workload scheduling strategy that allows the scheduler to make better use of available hardware resources by distributing computational jobs not strictly in the order in which they arrived to the system, but in a random order based on the size of the computational job. The main idea of the Backfill strategy is to "densely fill" the free resources with computing jobs from the queue for which there are enough free resources available at the moment. The Backfill strategy and its modifications make it possible to increase energy efficiency by maintaining a high level of server utilization. However, the effectiveness of this approach is significantly reduced in the case of low input workload intensity and low system utilization level, respectively, and, in addition, it does not take into account the individual characteristics of energy consumption and performance of computing nodes.

The authors of the study [30] proposed an approach to dynamic workload consolidation (consolidation of virtual machines (VMs) in a virtualized computing environment) and developed the OpenStack NEAT software based on it. The proposed VM consolidation algorithm solves 4 subproblems:

1. Makes a decision about the insufficient load of the system node (with the purpose of further moving all VMs from it and putting the node into sleep mode).
2. Makes a decision about an overloaded node to move part of the VM from it to other nodes in order to avoid system performance degradation.
3. Selects VMs to move from overloaded nodes.
4. Moves the selected VMs to other active or specially activated nodes.

Experimental validation of the approach has shown that dynamic workload consolidation is able to reduce overall power consumption with limited impact on computing performance. However, it is critically important to maintain a sufficient level of system availability, since an unexpected change in the input workload arrival rate can lead to a violation of the ICN workload processing requirements.

In [31], a number of horizontal scaling policies, such as NEVEROFF, INSTANTOFF, and SLEEP, were analysed. These policies are aimed at putting a certain number of servers into sleep mode, taking into account the workload distribution in the server cluster. The authors of the study [31] propose an energy-efficient DELAYEDOFF policy, according to which additional servers are turned on when new computing job arrives, for which there are not enough available resources, but are turned off only after a certain period of time after

processing the "excessive" workload. Horizontal scaling approaches can significantly save power by shutting down servers completely or putting them to sleep mode, but can negatively affect system performance and availability, especially in the case of dynamic changes in workload arrival rate, which is critical in view of the need to ensure that quality requirements are met. In addition, existing horizontal scaling and consolidation approaches do not take into account the individual power consumption characteristics of computing nodes, which leads to suboptimal use of computing resources.

Thus, there is a need to find a comprehensive systematic approach to increase the energy efficiency of ICN workload processing while meeting the requirements for performance and availability of the processing system in case of unpredictable dynamic changes of the input workload arrival rate and taking into account the individual energy consumption models of computing nodes.

Description of the researched ICN workload processing system

Let us consider a distributed computing system as part of the ICN, physically represented by a data center consisting of M server clusters, each of which in turn consists of N computing nodes. Each node N_j is described by parameters: V_{RAM_j} – amount of RAM [GB]; $V_{storage_j}$ – data storage volume [GB]; C_j – performance of the j -th node [workload units / s]; k_{cores_j} – the number of central processor (CPU) cores of the node [pcs]. Each of the computing nodes in the system can be in one of the following states: "active" - the node processes the workload and/or is able to accept new computing jobs for processing; "idle state" - the node is turned on, but does not process any computing job at the moment; "disabled" - the node is removed from the system by turning it off or driving to a sleep mode.

The input workload is a stream of discrete computing jobs entering the system at random moments in time. The unit of input workload is computational job. Physically, one job is represented as a single computing process of a computer. In the process of workload distribution, each computational job is characterized by the following parameters: $\Delta t_{max_j} = const[s]$ – the maximum time of job execution (if the job was not successfully processed by the time Δt_{max_j} it is removed from the system); the minimum required amount of resources to perform job: the minimum required amount of RAM

$V_{RAM_{min_i}}$ [GB]; the minimum required number of CPU cores $k_{cores_{min_i}}$ [cores]; minimum required volume of permanent data storage $V_{storage_{min_i}}$ [GB]. The input workload is characterized by its arrival rate – the amount of workload that enters the system per unit of time. Daily statistics of the input workload arrival rate on the system are given.

Based on the analysis of the processing requirements of various types of ICN workload, let us formulate indicators and efficiency criteria of the workload processing.

Energy efficiency of workload processing E_Σ is the amount of workload ω processed by the system of N nodes when consuming the amount of energy W . When processing the workload in N nodes, the total amount of energy is calculated as $W = \sum_{j=1}^N W_j$, and the energy efficiency of data processing is defined as:

$$E_\Sigma = \frac{\omega}{\sum_{j=1}^N W_j}. \quad (1)$$

The higher the value of this indicator, the more energy efficient the system is, since it can handle a larger amount of workload with a smaller amount of energy consumed.

Workload processing performance C_Σ is the amount of workload processed by the system per unit of time:

$$C_\Sigma = \frac{\omega}{T}, \quad (2)$$

where ω – amount of workload processed by the system; T – processing time.

The availability coefficient of the system p_{avail} as an indicator of its availability is the third performance indicator selected within our research based on the analysis of ICN workload processing requirements. Availability coefficient in a probabilistic definition (that is, in the case of its determination through mathematical expectations of working time and downtime) is related to the loss probability of a request p_{loss} according to the expression:

$$p_{avail} = 1 - p_{loss}.$$

If for some reason (for example, due to the lack of free data processing resources) the request was lost, it needs to be re-processed, which negatively affects QoS.

Let us analyse the relationship between these indicators based on their formal definitions. For example, consider two systems A and B with the same number of computing nodes N . Both systems must process the same volume of workload ω . Let the system A be more energy efficient (i.e. $E_{\Sigma_A} > E_{\Sigma_B}$). According to the formula (1), this means that the system A will spend a smaller amount of energy W on processing the workload ω . The amount of consumed energy W is directly related to the processing time, because according to the basic formula relating power and energy, the amount of energy is defined as $W = P \cdot T$. Then two options are possible:

1. System A spent less time on processing (i.e. $T_A < T_B$). Then, according to formula (2), the performance of such a system will also be greater ($C_{\Sigma_A} > C_{\Sigma_B}$).

2. The system A spent more or the same amount of time on processing (i.e. $T_A \geq T_B$). In this case, the lower amount of energy consumed by the system A is explained by the lower power consumption of the system ($P_A < P_B$), which is determined by the power consumption of its components (computing nodes) and the distribution of the workload between these components. Then, according to formula (2), the performance of the system A will be lower ($C_{\Sigma_A} < C_{\Sigma_B}$).

Based on this, it cannot be argued that the energy efficiency indicator E_Σ and the performance indicator C_Σ are in dialectical contradiction, and that an increase in one indicator necessarily leads to a decrease in the other or vice versa. Thus, it is desirable to maximize both indicators.

Based on this statement, we will formulate an efficiency criterion for the process under study:

$$K_{opt} = E_\Sigma \cdot C_\Sigma \rightarrow \max, \text{ at } p_{avail} \geq p_{avail_{SLA}},$$

where $p_{avail_{SLA}}$ is the minimum allowable value of the system availability coefficient according to the SLA agreement.

That is, in the set of possible configurations of the workload processing system, the most effective one is the one that allows obtaining the maximum value of the product of energy efficiency E_Σ and performance C_Σ indicators with a satisfactory value of the system availability coefficient p_{avail} .

In order to qualitatively describe the complex inter-relationships between the selected efficiency indicators and the parameters affecting them, an ontological model of the considered system was proposed, which is described in detail in a previous study [32]. For a quantitative description of these relationships, a mathematical model of the workload processing system in ICN in the form of a queuing system (QS) was built, which differs from the known ones in that it takes into account the variable nature of the input workload arrival rate and the possibility of using parallelization techniques in the development of modern ICN software. The mathematical model of the system is a QS with a finite queue and with losses, which is described by the following parameters:

– $k' = k / M(x)$ – the number of service channels, where $k = k_{cores}$ – the given number of computing cores in the system; $M(x)$ – mathematical expectation of the number of simultaneous requests x in the group. For a uniformly distributed random variable, the mathematical expectation is equal to $M(x) = \frac{X_{max} + X_{min}}{2}$;

X_{max} – the maximum number of processor cores of one server in the system under study (corresponding to the maximum possible number of cores that may be required by the computing job for processing); $X_{min} = 1$ is the minimum possible number of cores that may be required by the computing job for processing.

– $\lambda' = \frac{\int_{t_0}^{t_0+\Delta t} \lambda(t) dt}{\Delta t \cdot M(x)}$ is the arrival rate of incoming

requests for the time period $[t_0; t_0 + \Delta t]$, where $\lambda(t)$ is a given input workload curve.

– $\mu' = \frac{\sum_{i=1}^{k'} \sum_{j=1}^{M(x)} \mu_{ij}}{k'}$ is the average processing

rate, where $\mu_{ij} = \bar{\mu}_j$ is the average processing rate of the j -th computing core.

– $Q' = \frac{Q \cdot M(x)}{M(x)} = Q$ – queue length (coincides

with the given queue length).

The main efficiency indicators of the QS with a finite queue and with losses, the formal expressions for which can be obtained from Little's formulas [33], are:

– Probability of losing a request:

$$p_{loss} = p_{k'+Q} = \frac{\rho^{k'+Q}}{k'^Q \cdot k'!} p_0.$$

– Absolute bandwidth: $A = \lambda' (1 - \frac{\rho^{k'+Q}}{k'^Q \cdot k'!} p_0)$.

– The average number of queries in the queue:

$$L_Q = \frac{\rho^{k'+1} \cdot p_0 (1 - (Q+1 - Q \frac{\rho}{k'}) \cdot (\frac{\rho}{k'})^Q)}{k' \cdot k'! (1 - \frac{\rho}{k'})^2}.$$

– The average number of queries in processing, which corresponds to the average number of occupied service channels: $\bar{n} = \rho \cdot (1 - \frac{\rho^{k'+Q}}{k'^Q \cdot k'!} p_0)$, where $\rho = \lambda' / \mu'$.

A graphical representation of the constructed mathematical model of the ICN workload processing system is shown in Fig. 1. The constructed mathematical model is the basis of the proposed comprehensive method of energy-efficient workload processing in the ICN.

A comprehensive method of energy-efficient workload processing in the ICN

To solve the problem of increasing energy efficiency, performance and availability of the ICN workload processing system, a comprehensive method of energy-efficient workload processing is proposed, which includes the following steps:

1. Computing nodes' attestation and ranking;
2. Definition of horizontal scaling patterns;
3. Horizontal scaling and workload scheduling;
4. Prediction of workload deviations and patterns adaptation.

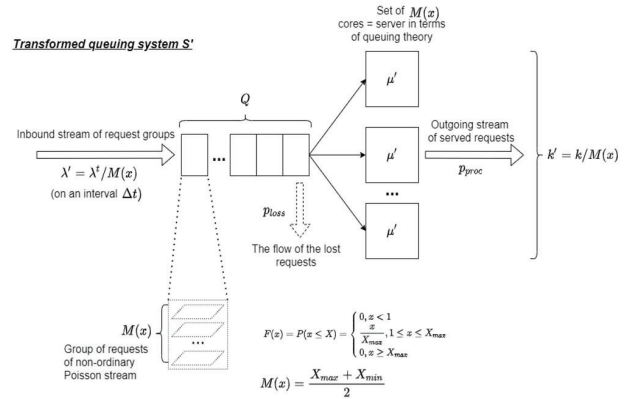


Fig. 1. Graphic representation of the constructed mathematical model of the ICN workload processing system

The main idea of the method is to provide the optimal amount of active computing resources in the system at every time moment with intensive use of the most energy-efficient computing nodes and their dens-

est filling in order to avoid resource idling. A schematic representation of the steps of the proposed comprehensive method is shown in Fig. 2.

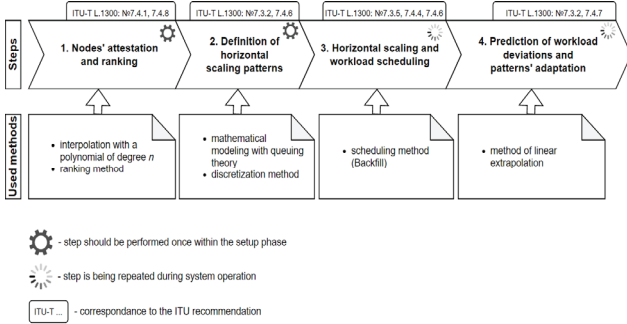


Fig. 2. Schematic representation of the steps of the proposed comprehensive method of energy-efficient ICN workload processing

1. Computing nodes' attestation and ranking

This step is performed once during the system setup phase. The purpose of the step is to determine the individual characteristics of energy consumption and performance of the computing nodes available in the system. The step is based on recommendations 7.4.1 and 7.4.8 of the International Telecommunication Union ITU-T L.1300 [24]. In order to obtain individual characteristics of energy consumption $P_j = f(CPU_j)$ for all computing nodes of the system as a function of CPU utilization, the so-called attestation of nodes is carried out. Two methods of attestation are analysed: a software-based approach, in which the nominal power consumption of the node components is summed up to obtain the total power consumption at different CPU utilization levels, and an empirical determination of power consumption patterns, in which the total power consumption is measured directly in the power chain of each node. The result of applying both methods is the energy consumption functions for each computing node of the system in tabular form. In order to obtain an analytical form of the functions, it is proposed to use the method of interpolation of the obtained functions with polynomial of a degree $n = m - 1$:

$$P_j(CPU_j) = a_0 + a_1 \cdot CPU_j^1 + a_2 \cdot CPU_j^2 + \dots + a_{m-1} \cdot CPU_j^{m-1},$$
where m is the number of interpolation nodes, which corresponds to the number of energy consumption measurements at constant CPU load levels; CPU_j – CPU load of the computing node; a_0, a_1, \dots, a_{m-1} – polynomial coefficients.

After the attestation, the nodes are ranked (sorted):

– Sorting by energy consumption indicator

$$S_j = \int_0^{100} P_j(CPU_j) dCPU_j.$$

– Sorting by the nominal value of nodes' performance indicator C_j .

As a result, we get a ranked list of nodes from the worst to the best according to the indicators S_j and C_j . More intensive use of nodes with better indicators S_j and C_j leads to an increase in the overall performance of the system C_Σ and a decrease in the total energy

consumption of the system $W = \sum_{j=1}^N W_j$ when processing the workload ω , $K_{opt} = E_\Sigma \cdot C_\Sigma \rightarrow \max$.

2. Definition of horizontal scaling patterns

This step is performed once during the system setup phase. The purpose of the step is to determine the so-called scaling patterns based on statistical data on the input workload arrival rate during the day. Scaling patterns determine the optimal number of active computing nodes in the system at each moment in time. The step is based on recommendations 7.3.2 and 7.4.6 of the International Telecommunication Union ITU-T L.1300 [24].

To determine scaling patterns, a constructed mathematical model of the system in the form of QS is used:

1. Given the maximum permissible probability of request loss $p_{lossSLA}$, the threshold values of the input workload arrival rate are determined according to the

$$\text{expression } \lambda_n(t) = \mu' \cdot n + Q \sqrt{\frac{p_{lossSLA} \cdot n^Q \cdot n!}{p_0}}, n \in \mathbb{N}^*,$$

where n is the number of computing nodes; μ' – average processing rate; Q – queue length; p_0 is the probability of the 0-th state of the QS.

2. For daily workload statistics for each of the intervals Δt corresponding to the transition from the value $\lambda_{n,i}(t)$ to $\lambda_{n,i+1}(t)$, the values of $\lambda' = \max(\lambda_i), \lambda_i \in [\lambda_{n,i}(t), \lambda_{n,i+1}(t)]$ are calculated.

3. For each of the intervals Δt , the minimum necessary number of computing nodes n is determined, at which the inequality

$$P_{loss} = \frac{\rho^{n+Q}}{n^Q \cdot n!} P_0 = \frac{\left(\frac{\lambda'}{\mu'}\right)^{n+Q}}{n^Q \cdot n!} P_0 < P_{loss_{SLA}} \text{ will be met at } \lambda' = \max(\lambda_i), \lambda_i \in [\lambda_{n,i}(t), \lambda_{n,i+1}(t)].$$

The individual energy consumption functions of the system nodes obtained in step 1 are used to determine the total estimated energy consumption of the system with the number of active nodes n .

As a result of applying the step, we get the minimum required number of active computing nodes n in the time interval Δt to meet the requirements for system availability $p_{avail} \geq p_{avail_{SLA}}$ while reducing the total power consumption $P_{\Sigma} = \sum_{j=1}^N P_j(CPU_{avg_j}) \rightarrow \min$.

3. Horizontal scaling and workload scheduling

Execution of this step is repeated regularly in the process of ICN workload processing, and it is based on recommendations 7.3.5, 7.4.4 and 7.4.6 of the International Telecommunication Union ITU-T L.1300 [24].

Within the step 3 for each time interval Δt ($N-n$) nodes are put to a sleep mode. At the same time, n active nodes are selected from the ranked list according to indicators S_j and C_j (see Step 1). The Backfill workload scheduling algorithm is used to distribute computing jobs between the remaining active nodes.

As a result, a reduction in the total power consumption of the system is ensured $P_{\Sigma} = \sum_{j=1}^N P_j(CPU_{avg_j}) \rightarrow \min$ by putting $(N-n)$ the least effective according to indicators S_j and C_j nodes into a sleep mode. The increase in system performance occurs due to the consolidation of the workload on active nodes ($CPU_j \rightarrow \max, T \rightarrow \min$ at $\omega = const$).

Thus, minimization of the total power consumption of the system P_{Σ} leads to a decrease in the total energy

consumption of the system $W = \sum_{j=1}^N W_j$ and, as a result,

an increase in the energy efficiency index E_{Σ} at a constant workload volume ω . The use of the Backfill algorithm provides processing of the workload volume ω in less time T due to dense placement of jobs on nodes, i.e. $CPU_j \rightarrow \max$, which causes an increase in performance C_{Σ} .

4. Prediction of workload deviations and patterns' adaptation

The execution of this step is also repeated regularly in the process of the ICN workload processing. It is based on recommendations 7.3.2 and 7.4.7 of the International Telecommunication Union ITU-T L.1300 [24]. The purpose of this step is to detect the deviation of the current workload arrival rate from the statistical and dynamic adjustment of the scaling patterns.

At the moment t when a deviation in the arrival rate of the current workload $\lambda_{obs}(t)$ from the statistical arrival rate $\lambda_{pred}(t)$ by more than σ is detected, the value of the so-called adaptation window is calculated, the concept of which is proposed in the paper [34]:

$$W(t) = I_{base} - K \cdot \frac{\sum_{j=t-h}^{t-1} \max(\sigma; |\lambda_{obs}(t) - \lambda_{pred}(t)|)}{h-1} \cdot I_{base}; \quad (3)$$

$$K = \begin{cases} 0, & \sigma > |\lambda_{obs}(j) - \lambda_{pred}(j)|, \\ const, & \sigma \leq |\lambda_{obs}(j) - \lambda_{pred}(j)|, \end{cases}$$

where I_{base} is the basic monitoring period; σ – permissible deviation of input workload arrival rate; $\lambda_{obs}(t)$ – workload arrival rate observed at the time t ; $\lambda_{pred}(t)$ – expected (predicted) workload intensity at the moment of time t , according to the workload statistics curve; h – the number of previous monitoring intervals determined by the algorithm (this value can be chosen depending on the features of the system, in particular, the possibilities for storing monitoring results); K is the normalization constant, which is determined for each system individually and ensures the non-negativity of expression (3). K should be determined in such a way that with any realistically possible deviations of $\lambda_{obs}(t)$ from $\lambda_{pred}(t)$ the inequality

$$\frac{\sum_{j=t-h}^{t-1} \max(\sigma; |\lambda_{obs}(t) - \lambda_{pred}(t)|)}{h-1} < \frac{1}{K}$$

is fulfilled.

After that, using the extrapolation method, the predicted arrival rate of the workload is determined, taking into account the deviation at the moment of time $(t + \Delta t)$, which corresponds to the next scaling pattern change moment:

$$\lambda_{pred}(t + \Delta t) = \lambda_{base_{pred}}(t + \Delta t) + \sum_{j=t-h}^{t-1} \frac{\lambda_{obs}(j) - \lambda_{pred}(j)}{h-1},$$

where $\lambda_{base_{pred}}(t + \Delta t) = \max(\lambda_i), \lambda_i \in [\lambda_{n,i}(t), \lambda_{n,i+1}(t)]$ – the maximum value of the input workload arrival rate ac-

according to statistics for the period for which the scaling pattern should be adjusted (between adjacent threshold values, $\lambda_n(t)$ respectively); $\sum_{j=t-h}^{t-1} \frac{\lambda_{obs}(j) - \lambda_{pred}(j)}{h-1}$ – average

deviation of workload arrival rate observed during h previous monitoring intervals.

Based on the predicted arrival rate, the scaling pattern is recalculated at $\lambda' = \lambda_{pred}(t + \Delta t)$. The procedure is suggested to be repeated at every moment $(t + W(t))$.

As a result of the regular execution of step 4, the adaptation of the scaling patterns corresponds to the dynamically changing input workload arrival rate $\lambda_{pred}(t + \Delta t)$. At the same time, the requirements for system availability are met $p_{avail} \geq p_{avail_{SLA}}$, which is especially important for time-critical types of ICN workloads.

Thus, unlike the existing approaches, the proposed comprehensive method takes into account individual models of computing nodes' energy consumption, combines the advantages of horizontal scaling and energy-efficient scheduling approaches, takes into account the possibility of unpredictable dynamic changes in the input workload arrival rate.

Experimental verification of the proposed comprehensive method's effectiveness

On the basis of the proposed comprehensive method of energy-efficient workload processing in the ICN, the computer resource management software was developed, the component diagram of which is shown in Fig. 3.

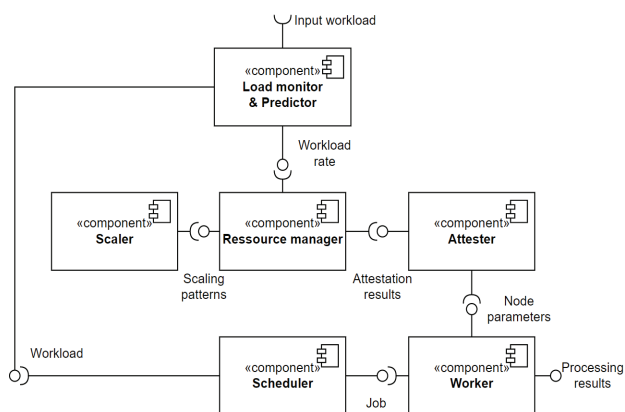


Fig. 3. Component diagram of computing resource management software based on the proposed comprehensive method

The developed software can be integrated into the

5G ICN architecture, namely, be used in distributed data centers of the edge cloud to solve the problems of Edge Computing and the central cloud to solve the problems of SDN, NFV, Network Slicing, bDDN.

In order to evaluate the effectiveness of the proposed comprehensive method, a laboratory experiment was conducted on the basis of a server cluster with four computing nodes.

Table 1. Input data for the experiment

Parameter	Description
$n = 4$	The number of computing nodes
$C_j = \{8715.73, 8715.73, 7518.75, 13319.62\}Pt$	Nominal performance of nodes
$Q = 5$	Queue length [computing jobs or QS applications]
$CPU_{max_j} = 75\%$	Average CPU utilization of nodes when using Backfill [34]
$\mu'_{avg} = 0,03$	Average request processing rate [computational operations per second] (per 1 core)
$P_{loss_{SLA}} = 5 \cdot 10^{-2}$	The maximum permissible probability of losing an job
$k' = 7 \cdot 4 = 28$	The number of QS servers (the average number of node cores is 7)

The experiment was carried out according to the following plan:

1. Evaluation of the proposed comprehensive method:

- a. preparatory phase (attestation and ranking of nodes, scaling patterns' definition);
- b. main phase (horizontal scaling and workload scheduling, prediction of workload deviations and patterns adaptation).

2. Evaluation of the energy-efficient Backfill scheduling algorithm [26] (comparison with the proposed comprehensive method).

3. Evaluation of the Round Robin scheduling algorithm [36] (comparison with the proposed comprehensive method).

The results of an experimental comparison of the proposed comprehensive method with the existing Backfill approach to energy-efficient workload scheduling showed that the proposed comprehensive method allows achieving a gain of 9.953% in terms of energy efficiency compared to Backfill. At the same time, the gain in terms of performance is 5.593% when meeting the requirements for the permissible value of the system availability coefficient according to the SLA. Accord-

ing to the proposed efficiency criterion K_{opt} the gain constituted 15.722%. An experimental comparison of the proposed comprehensive method with the widely used Round Robin workload scheduling approach showed that the proposed method gained 26.382% in terms of energy efficiency and 49.458% in terms of performance. According to the proposed efficiency criterion K_{opt} the gain constituted 88.887%. The obtained results are mainly due to the use of the improved method of horizontal scaling proposed in the research using individual energy consumption models of system nodes, as well as the method of adapting scaling patterns to dynamic changes in the intensity of the input workload.

Conclusions

The analysis of the requirements for the ICN workload processing based on the specifications and recommendations of the International Telecommunication Union and the European Institute of Telecommunication Standards showed that the problem of increasing energy efficiency, performance and availability of computing infrastructure in ICN is very important nowadays. At the same time, the problem of ensuring the energy efficiency of workload processing systems is becoming particularly relevant in view of the tendency towards a rapid increase in energy consumption of such systems.

The analysis of existing approaches to increase the energy efficiency of workload processing revealed some of their shortcomings, namely: existing approaches do not take into account the individual energy consumption characteristics of computing nodes and do not pay enough attention to the system availability indicator under the circumstances of unpredictable dynamic changes in workload arrival rate, which is critically important for the ICN workload.

A comprehensive method of energy-efficient ICN workload processing is proposed, which differs from existing approaches by using individual energy consumption models of system computing nodes, combining the advantages of horizontal scaling approaches and energy-efficient workload distribution, taking into account dynamic changes in the input workload arrival rate, which made it possible to increase the energy efficiency and performance of the workload processing, subject to compliance with system availability requirements.

Proposed method and the software developed on its basis can be integrated into the 5G ICN architecture, namely, be used in distributed data centers of the edge cloud to solve the problems of Edge Computing and the central cloud to solve the problems of SDN, NFV, Net-

work Slicing, bDDN.

Experimental verification of the proposed comprehensive method's efficiency showed that it allows achieving a gain of 15.722% according to the proposed efficiency criterion K_{opt} in comparison with the known Backfill energy-efficient workload scheduling strategy and a gain of 88.887% in comparison with the common Round Robin workload scheduling approach, respectively.

The future research in this area, consists of a more detailed analysis of individual types of ICN workloads and their requirements. Furthermore, the topic of mixed workload streams and job prioritization based on workload typing deserves further research.

References

1. The law of Ukraine About telecommunications, retrieved from <https://zakon.rada.gov.ua/laws/show/1280-15#Text>. [last accessed 11.10.2020].
2. View on 5G Architecture: 5G PPP Architecture Working Group, (2019), retrieved from https://5g-ppp.eu/wp-content/uploads/2019/07/5G-PPP-5G-Architecture-White-Paper_v3.0_PublicConsultation.pdf [last accessed 18.02.2022].
3. ITU-T Recommendation Y.3300, (2014), "Framework of software-defined networking", retrieved from <https://www.itu.int/rec/T-REC-Y.3300-201406-I/en> [last accessed 16.09.2022].
4. ETSI Standard GR NFV 003, (2020), "Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV", retrieved from https://www.etsi.org/deliver/etsi_gr/NFV/001_099/003/01.05.01_60/gr_NFV003v010501p.pdf [last accessed 16.09.2022].
5. Khan, L.U., Yaqoob, I., Tran, N.H., Han, Z. and Hong, C.S., (2020), "Network slicing: Recent advances, taxonomy, requirements, and open research challenges", *IEEE Access*, 8, pp. 36009-36028. DOI: <https://doi.org/10.1109/ACCESS.2020.2975072>
6. Bravo, C., Bäckström, H. (2020), "Edge computing and deployment strategies for communication service providers", *White Paper, Ericsson*.
7. ITU-T Recommendation Y.3652, (2020), "Big data driven networking - requirements", retrieved from <https://www.itu.int/rec/T-REC-Y.3652> [last accessed 16.09.2022].
8. ITU-T Recommendation L.1360, (2016), "Energy control for the software-defined networking architecture", retrieved from <https://www.itu.int/rec/T-REC-L.1360/en> [last accessed 17.09.2022].
9. ITU-T Recommendation L.1361, (2018), "Measurement method for energy efficiency of network functions

- virtualization”, retrieved from <https://www.itu.int/rec/T-REC-L.1361> [last accessed 13.09.2022].
10. Soós, G., Ficzer, D., Varga, P. and Szalay, Z., (2020), “Practical 5G KPI measurement results on a non-standalone architecture”, *In Noms 2020 IEEE/IFIP network operations and management symposium*, pp.1-5. DOI:<https://doi.org/10.1109/NOMS47738.2020.9110457>
11. Khan, L.U., Yaqoob, I., Tran, N.H., Han, Z. and Hong, C.S., (2020), “Network slicing: Recent advances, taxonomy, requirements, and open research challenges”, *IEEE Access*, 8, pp. 36009-36028. DOI: <https://doi.org/10.1109/access.2020.2975072>
12. ITU-T Recommendation Y.3156, (2020), “Framework of network slicing with AI-assisted analysis in IMT-2020 networks”, retrieved from https://www.itu.int/rec/dologin_pub.asp?lang=s&id=T-REC-Y.3156-202009-I!!PDF-E&type=items [last accessed 13.09.2022].
13. ITU-T Recommendation Y.3111, (2017), “IMT-2020 network management and orchestration framework”, retrieved from <https://www.itu.int/rec/T-REC-Y.3111/en> [last accessed 17.09.2022].
14. ITU-T Recommendation b-ITU-T Y.2701, (2017), “Security requirements for NGN release 1”, retrieved from <https://www.itu.int/rec/T-REC-Y.2701/en> [last accessed 17.09.2022].
15. ETSI Standard TR 132 972, (2020), “5G; Telecommunication management; Study on system and functional aspects of energy efficiency in 5G networks (3GPP TR 32.972 version 16.1.0 Release 16)”, retrieved from https://www.etsi.org/deliver/etsi_tr/132900_132999/132972/16.01.00_60/tr_132972v160100p.pdf [last accessed 16.09.2022].
16. ITU-T Recommendation F.743.12, (2021), “Requirements for edge computing in video surveillance”, retrieved from <https://www.itu.int/rec/T-REC-F.743.12/en> [last accessed 13.09.2022].
17. ITU-T Recommendation F.743.10, (2019), “Requirements for mobile edge computing-enabled content delivery networks”, retrieved from <https://www.itu.int/rec/T-REC-F.743.10>.
18. ITU-T Recommendation Y.3652, (2020), “Big data driven networking – requirements”, retrieved from <https://www.itu.int/rec/T-REC-Y.3652>.
19. ITU-T Recommendation Y.2704, (2010), “Security mechanisms and procedures for NGN”, retrieved from <https://www.itu.int/rec/T-REC-Y.2704/en>.
20. Ericsson, (2020), “5G for business: a 2030 market compass”, retrieved from <https://www.ericsson.com/assets/local/5g/the-5g-for-business-a-2030-compass-report-2019.pdf>
21. Masanet, E., Shehabi, A., Lei, N., Smith, S. and Koomey, J., (2020), “Recalibrating global data center energy-use estimates”, *Science*, 367(6481), pp.984-986. DOI: <https://doi.org/10.1126/science.aba3758>
22. Yole Développement, APEC, (2016), “Data Center Market and Technology Trends Power Electronics presentation”, retrieved from https://www.slideshare.net/Yole_Developpement/data-center-market-and-technology-trends-power-electronics-presentation-held-at-apec-2016-from-yole-dveloppement
23. Vasilevskyi, O. M., Podzharenko V. O., (2010), “Standardization of reliability indicators of technical means: study guide” / O. M. Vasilevskyi, V. O. Podzharenko. – Vinnytsia: VNTU, 2010. – 129 p.
24. ITU-T Recommendation L.1300, (2014), “Best practices for green data centers”, retrieved from <https://www.itu.int/rec/T-REC-L.1300/en>.
25. L.A. Barroso, U. Hölzle, (2007), “The Case for Energy-Proportional Computing”, in *Computer*, vol. 40, no. 12, pp. 33-37, DOI: <https://doi.org/10.1109/MC.2007.443>
26. G. Blokdyk, IBM docs, (2022), “IBM Spectrum LSF 10.1.0 Documentation”, retrieved from <https://www.ibm.com/docs/en/spectrum-lsf/10.1.0?topic=jobs-backfill-scheduling>
27. V.V. Mazalov, N.N. Nikitina, (2012), “Evaluating the characteristics of the Backfill algorithm when managing the flow of tasks on a computational cluster,” *Computing technologies*, 2012.
28. Suresh, A. and Vijayakarhick, P., (2011), “Improving scheduling of Backfill algorithms using balanced spiral method for cloud metascheduler”, In *2011 International Conference on Recent Trends in Information Technology (ICRTIT)*, pp. 624-627. DOI: <https://doi.org/10.1109/ICRTIT.2011.5972255>
29. G. Lawson, E. Smirni, and D. Puiu, (2002), “Self-adapting Backfilling scheduling for parallel systems,” in *International Conference on Parallel Processing*, pp. 583-592. DOI: <https://doi.org/10.1109/ICPP.2002.1040916>
30. Beloglazov and R. Buyya, (2015), “OpenStack Neat: a framework for dynamic and energy-efficient consolidation of virtual machines in OpenStack clouds”, *Concurr. Comput.*, vol. 27, no. 5, pp. 1310–1333. DOI: <http://dx.doi.org/10.1002/cpe.3314>
31. Gandhi, V. Gupta, M. Harchol-Balter, and M.A. Kozuch, (2010), “Optimality analysis of energy-performance trade-off for server farm management,” *Perform. eval.*, vol. 67, no. 11, pp. 1155–1171. DOI: <https://doi.org/10.1016/j.peva.2010.08.009>

32. L. Globa, N. Gvozdetska, and R. Novogrudska, (2021), "Ontological model for data processing organization in information and communication networks," *Syst. Res. Inf. Technol.*, no. 1, pp. 47–60. DOI: <http://dx.doi.org/10.20535/SRIT.2308-8893.2021.1.04>
33. Kremer, N.S., Putko, B.A., Trishyn, I.M., Fridman, M.N. (2017), "Research of operations in economics: a textbook for universities", Ed. Yurayt, Moscow, 438 p. [Кремер, Н.Ш., Путко, Б.А., Тришин, И.М., Фридман, М.Н. (2017), "Исследование операций в экономике: учебник для вузов", Издательство Юрайт, Москва, 438 с.]
34. Sulima, S. and Skulysh, M., (2017), "Hybrid resource provisioning system for virtual network functions", *RADIO ELECTRONICS COMPUTER SCIENCE CONTROL*, (1), pp.16-23. DOI: <http://dx.doi.org/10.15588/1607-3274-2017-1-2>
35. Mu'alem, A.W. and Feitelson, D.G., (2001), "Utilization, predictability, workloads, and user runtime estimates in scheduling the IBM SP2 with backfilling", *IEEE transactions on parallel and distributed systems*, 12(6), pp.529-543. DOI: <https://doi.org/10.1109/71.932708>
36. Parashar, J. and Sharma, D.A., (2018), "A comparative study of different load balancing techniques", *International Journal of Engineering and Technology (UAE)*, 7(4.12), 63 p. DOI: <http://dx.doi.org/10.14419/ijet.v7i4.12.20994>

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Комплексний метод енергоефективного обслуговування навантаження в інформаційно-комунікаційній мережі

Проблематика. Особливості навантаження сучасної інформаційно-комунікаційної мережі (ІКМ) визначають специфічні вимоги щодо енергоефективності, продуктивності та доступності систем його обслуговування. Існуючі підходи щодо підвищення енергоефективності та продуктивності обслуговування навантаження не враховують можливості динамічних змін інтенсивності навантаження в мережі та індивідуальних характеристик енергоспоживання окремих обчислювальних вузлів системи.

Мета досліджень. Підвищення енергоефективності та продуктивності обслуговування навантаження ІКМ при забезпеченні вимог щодо доступності системи обслуговування з урахуванням динамічних змін інтенсивності вхідного навантаження та індивідуальних характеристик енергоспоживання обчислювальних вузлів.

Методика реалізації. Побудовано математичну модель системи обслуговування навантаження із застосуванням методів теорії масового обслуговування, а також онтологічну модель цієї системи із застосуванням методів інтелектуального аналізу даних, що дозволило кількісно та якісно описати складні зв'язки між параметрами системи та показниками ефективності обслуговування навантаження. На основі побудованих моделей запропоновано комплексний метод енергоефективного обслуговування навантаження, що відрізняється від відомих використанням індивідуальних моделей енергоспоживання обчислювальних вузлів системи, поєднанням переваг підходів горизонтального масштабування та енергоефективного планування навантаження з урахуванням динамічних змін інтенсивності навантаження.

Результати досліджень. Ефективність обслуговування навантаження ІКМ підвищено на 15,722% за критерієм ефективності, який включає показники енергоефективності та продуктивності, у порівнянні з відомим енергоефективним підходом Backfill при дотриманні вимог щодо доступності системи обслуговування.

Висновки. Енергоефективність, продуктивність та доступність системи обслуговування навантаження ІКМ може бути покращено за рахунок поєднання підходів горизонтального масштабування та енергоефективного планування задач із використанням індивідуальних моделей енергоспоживання обчислювальних вузлів та при врахуванні динамічних змін інтенсивності вхідного навантаження.

Ключові слова: енергоефективність; продуктивність; доступність; навантаження; ІКМ.