INCREASE THE EFFICIENCY OF SERVICING THE FLOWS OF COMPOSITE REQUESTS BY NODES DISTRIBUTED IN CONDITIONS OF NON-STATIONARY INTENSITY QUERIES

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Abstract: The article presents an approach to the study of decentralized maintenance of high-intensity composite queries in distributed data delivery systems. The goal is to increase the efficiency of servicing the flows of composite requests by nodes distributed in conditions of non-stationary intensity, due to the decentralized formation of logical groups of nodes. Mathematical modeling of queuing systems was used, theory and methods of mutual coordination were applied, and the mechanism of multi-agent systems was implemented. A mathematical model has been obtained and investigated, algorithms for the system operation have been constructed, and a simulation study of the results achieved has been conducted. The experimental results show an increase of 3.5-4.2% (depending on the number of nodes in the logical group) in the responsiveness of servicing the test flow of composite requests (reducing the average response time of a node) by the architecture of a multi-node distributed data collection system developed (in comparison with servicing the specified flow by a set of autonomous nodes.

Key words: Composite queries, non-stationary intensity, data delivery, logical groups of nodes, simulation study.

1. INTRODUCTION

Progress in the field of distributed computing is associated with the development and improvement of methods, mathematical, software and hardware at different levels

of the hierarchy of computing systems, from multicore and multiprocessor circuits to distributed computing systems of various functionality.

One of the most important components is a system that supports temporary local or distributed storage of up-to-date data required by their consumers. Its purpose is the prompt and timely provision of data required for the implementation of computing processes at various levels of their hierarchy. The main principle of its organization is data catching and support for their delivery protocols. At the same time, the levels of caching stores of such a system correspond to the levels of organization of distributed computing systems. Such systems include: multi-core micro cache memory system- and multiprocessor computers (CCS) [1], systems for updating routing tables in packet-switched communication systems [2], a subsystem for servicing distributed transactions in relational database management systems [3] and in systems based on microservice architecture, message queuing systems for distributed real-time information processing systems (MQS) [4], artificial intelligence systems with Federated Machine Learning Systems (FMLS) [5], content delivery systems, deployed by Internet service providers (CDN) [6]. Similar principles of the structural and functional organization of such systems allow them to be classified into a generalized class called data delivery systems (DDS).

The main research problems in the DDS domain are problems of ensuring consistency and accessibility of the delivered data, which is reflected in the development of a theoretical framework, for example, the CAP (Consistency, Availability, Partition tolerance) [7] and BASE (Fundamentally Available, Soft-state, Eventually consistent) theorems for systems with stable and unstable states, respectively. At the same time, such DDS studies do not fully consider the property of data delivery efficiency, summarized by the indicator "response time of the DDS node to a data delivery request", mainly focus on centralized management of the delivery process and do not fully take into account autonomy their components (nodes) related to the structural and functional evolution of the distributed computing systems to which they belong. Thus, in the case of cache coherence in microprocessors, the problem of minimizing the response time of the local cache of a given core is solved by hardware implementation of delivery protocols, while in distributed computing systems such as MSQ, FMLS, CDN, where individual nodes or their federations have a high level of autonomy, there is practically no generalized solution to such an optimization problem, especially in conditions of servicing composite (containing parallel subqueries) streams of high-intensity queries.

At the same time, the proposed methods and algorithms are focused on distributed computing infrastructures with a deterministic or low-dynamic structure, while others formalize the optimization problem of consistency of data delivery under constraints, which in some cases is unacceptable for modern implementations of distributed computing systems with autonomous nodes (microservices, content delivery networks).

The goal is to increase the efficiency of servicing composite query flows by nodes of distributed data delivery systems in conditions of unstable intensity, through the

development of mathematical and software for the decentralized formation of logical groups of data delivery nodes.

2. MATHEMATICAL MODEL

As part of the solution to the problem of developing mathematical support for the process of servicing the flow of requests for data delivery in conditions of non-stationary intensity, the following tasks were performed: a formal representation of a distributed DDS as a set of autonomous subsystems (nodes) serving their own streams of requests for $Z_{\Delta DN}$ data delivery, as well as modeling the process of servicing such requests by a separate DDS node. The M/G/1 class was chosen as the base class of the queuing system (QS) models (Figure 1, a).

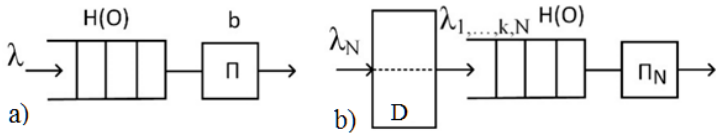

Figure 1. M/G/1 DDS system node model: a) basic view, b) with an additional node like "Query Manager"

The rationale is made that the $Z_{\Delta DN}$ request for a generalized DDS node can be represented by a random variable X having a heavy-tailed distribution:

$$\Pr\{X>x\} \sim x^{-\alpha}, \tag{1}$$

where $x\to\infty$ and $0<\alpha<2$ are the coefficient of variation of the random variable and $k\le x\le p$, k is the minimum query size, and p is the maximum query size.

The value of the $Z_{\Delta DN}$ request, which affects the time it is serviced by the device N, can be represented by a three-parameter Pareto distribution [8] with boundaries k and p with a probability distribution density function:

$$f(x;k,p,\alpha)=\frac{\alpha k^{\alpha}}{1-\left(\frac{k}{p}\right)^{\alpha}}x^{-\alpha-1} \tag{2}$$

A similar representation using the coefficient $\alpha\approx 2$ made it possible to model the average degree of variability of x (query size), and at $\alpha\to 0$ - an increase in the degree of its variability. Then the j-th moment of the device servicing N of some arbitrary request x is expressed as:

$$E\left[X^{j}\right]=\begin{cases}\dfrac{\alpha p^{j}\left(\left(\frac{k}{p}\right)^{\alpha}-\left(\frac{k}{p}\right)^{j}\right)}{(j-\alpha)\left(1-\left(\frac{k}{p}\right)^{\alpha}\right)}, j\neq\alpha\\ \dfrac{\alpha k^{\alpha}\ln\left(\frac{p}{k}\right)}{\left(1-\left(\frac{k}{p}\right)^{\alpha}\right)}, j=\alpha\end{cases} \tag{3}$$

Based on this, the probabilistic-temporal characteristics of the proposed QS were determined (Figure 1, a), such as: W' is the average waiting time; l is the length of the queue of waiting requests; E[x] is the load of the device. Since the queue length l according to Little's law can be expressed in terms of the average the waiting time is $l=\lambda W'$, then for the average variability of the request value (the second moment of the X value), according to the Pollachek-Khinchin formula [9], an expression is obtained for the average waiting time for processing the request $Z_{\Delta DN}$:

$$W'=\frac{\lambda E\left[X^2\right]}{2(1-\rho)}, \tag{4}$$

where ρ is the average number of requests served by the device Π and expressed as $\rho=\lambda b<1$, b is the parameter of the exponential law of the distribution of the duration of servicing requests.

For a Pareto distribution with finite moment boundaries, there are difficulties associated with the Laplace transform for such indicators as queue length and the busy time of the device G when servicing the request. It is proposed to approximate the Pareto distribution by a hyperexponential distribution [11] with the probability distribution density of some of its R-th part:

$$H_R(t)=\sum_{i=1}^{R} P_i\lambda_i e^{-\lambda_i t}, \text{ where } \sum_{i=1}^{R} P_i = 1 \tag{5}$$

Let's perform the Laplace transform on $H_R(t)$:

$$F_{H_R}(s)=L\left\{H_R(t)\right\}=\int_0^{\infty} e^{-st}H_R(t)dt=\sum_{i=1}^{R}\frac{P_i\lambda_i}{\lambda_i+s}, \tag{6}$$

where $s=\sigma+i\omega$ is a complex variable.

We obtain an expression for the nth moment of the distribution of the intervals for servicing requests by the device N performed on the basis of the expression:

$$E\left[X^n\right]=(-1)^n\frac{d^nL\left\{H_R(t)\right\}}{ds}|_{s=0}, \tag{7}$$

where X is a continuous random variable with probability density $H_R(t)$.

Accordingly, for the first and second moments of the distribution, the expression will take the form:

$$E[X]=\sum_{i=1}^{R}\frac{P_i}{\lambda_i},\ E\left[X^2\right]=\sum_{i=1}^{R}\frac{2P_i}{\lambda_i^2} \tag{8}$$

Similarly, we obtain the Laplace transform [12] for the waiting time for requests in the device queue Π:

$$L_W(s)=\frac{s(1-\rho)}{s-\lambda+\lambda L\left\{H_R(t)\right\}}=\frac{s(1-\rho)}{s-\lambda+\lambda\sum_{i=1}^{R}\frac{P_i\lambda_i}{\lambda_i+s}} \tag{9}$$

The value of the distribution density of waiting requests in the device queue Π – w(t) is obtained, and, accordingly, a generalized (cumulative) distribution function of waiting time W(t) is determined with its help.

3. MODEL INVESTIGATION

For the considered QS scheme (Figure 1, a), it is determined that it does not provide for the composite nature of $Z_{\Delta DN}$ queries, where their magnitude is distributed in the range of k and p values with a certain coefficient of variation α. It is proposed to represent the request Π arriving at the QS input with a certain intensity λ_N by a set of k particular requests with intensities $\lambda_{1,N}$, $\lambda_{2,N}$, ..., $\lambda_{k,N}$. In this regard, during modelling, this scheme was modified by adding node D (Dispatcher), which has the ability to split the incoming $Z_{\Delta DN}$ request into its constituent subqueries. Such a solution provides the ability to service these private requests both by a service device and redirect them to other service devices (distributed DDS nodes) (Figure 1, b). In order to model composite $Z_{\Delta DN}$ requests, it was proposed to consider the DDS model as a set of single-channel QS of class M/G/1, which makes it possible to implement in node D the function of redirecting private requests between nodes in conditions when the intensity of composite requests exceeds a certain acceptable threshold (for example, the conditions of the QoS SLA are not met). A modification of the QS model for a three-node DDS is shown in Figure 2.

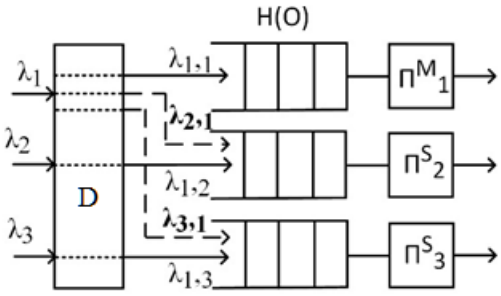

Figure 2. Proposed QS for subquery maintenance

In accordance with the proposed function of node D, in such a case, a subset of particular requests (in Figure 2, their intensities are $\lambda_{2,1}$, $\lambda_{3,1}$) will be redirected to the devices Π_2^S and Π_3^S responsibly. The M and S indexes in the names of devices associated with P2P peer-to-peer agreements denote Master (a device whose load is redistributed) and Slave (a device that processes part of the load of the Master device). Since the load served by the device Π_N^S from the Π^M device is additional, a priority system for servicing requests without displacement with p priority queues has been introduced. An expression is obtained for the waiting time for priority requests for an arbitrary queue p:

$$W_p = \frac{W_0}{(1-\sigma_p)(1-\sigma_{p+1})}, \tag{10}$$

where $\sigma_p = \sum_{i=p}^{P} \rho_i$, $W_0 = \sum_{i=p}^{P} \frac{\rho_i E\left[X_i^2\right]}{2}$ is the average waiting time for a priority request, depending on the time for servicing other priority requests, and $E\left[X_i^2\right]$ is the second time for servicing a request with the i-th priority.

It can be seen from (10) that the waiting time for a W_k request with the kth priority does not depend on the waiting time for requests with a lower priority. An expression is obtained for the waiting time for requests with an arbitrary p-th priority arriving at the Π^M master device. We denote the Laplace transform for the waiting time for such requests as $W_p^*(s)$, and $\lambda_L = \sum_{j=1}^{p-1} \lambda_{j,j}$, then:

$$W_p^*(s) = \frac{(1-\rho)s+\lambda_L\left[1-\sum_{j=1}^{p-1}\frac{\lambda_{j,j}}{\lambda_L}B_j^*(s)\right]}{s-\lambda_{p,p}+\lambda_{p,p}B_j^*(s)}, \quad (12)$$

An expression for the waiting time for requests with an arbitrary p-th priority arriving at any Π^S device serving requests with a priority in the range 1, 2, ..., p-1:

$$W_j^*(s) = \frac{(1-\rho)\left[s+\lambda_{p,p}-\lambda_{p,p}G_p^*(s)\right]}{s-\sum_{j=1}^{p-1}\lambda_{j,j}+\sum_{j=1}^{p-1}\lambda_{j,j}B_j^*(s+\lambda_{p,p}-\lambda_{p,p}G_p^*(s))}, \quad (13)$$

where $G_p^*(s) = B_j^*\left(s+\lambda_{p,p}-\lambda_{p,p}G_p^*(s)\right)$ is the transformation for allocating the service time by an arbitrary Π^S device for a request with the p-th priority.

Let's consider an algorithm for combining nodes of a distributed data delivery system and their mutual information coordination, which ensure the dynamic formation of logical groups of nodes serving high intensity flows of composite requests from data consumers.

A generalized scheme of the developed algorithm consists of a method for the dynamic formation of logical node groups (L_{DDS}) based on P2P interaction and an auction scheme for the inclusion of nodes in the L_{DDS} group, implemented according to a combined scheme with centralized initialization and completion of the auction and decentralized decision-making on the node's participation in the L_{DDS} group. When developing the algorithms, a generalized scheme of mutual information coordination of DDS nodes was considered, as well as the theory of auction games was developed, within the framework of which the type of auction was defined – the Vickrey auction [13].

Due to the peculiarities of the functional scheme for redirecting part of composite requests (Figure 2), a modification of the Vickrey auction scheme was proposed – a reverse Vickrey auction with multiple sellers and one buyer, and the functional components of such a scheme based on a multi-agent approach were identified.

4. ARCHITECTURE OF A MULTI-NODE DISTRIBUTED DDS

The architecture of a software-implemented multi-node distributed DDS is proposed, containing an overlay computing infrastructure that provides: initialization and completion of an auction for the formation of a logical group and support for peer-to-peer inter-network interaction of a subset of DDS nodes (logical group) in the process of their mutual information coordination.

The overlay nature of the proposed architecture makes it software-invariant to specific DDS implementations. For the DDS of the SRB data service layer, it can be implemented on the basis of application frameworks such as PyMAS (Python Multiagent System), for the SRB hardware layer – in the form of problem-oriented ASIC modules. A generalized diagram of the DDS node with the proposed overlay block for forming a logical group (marked with a dotted line) is shown in Figure 3.

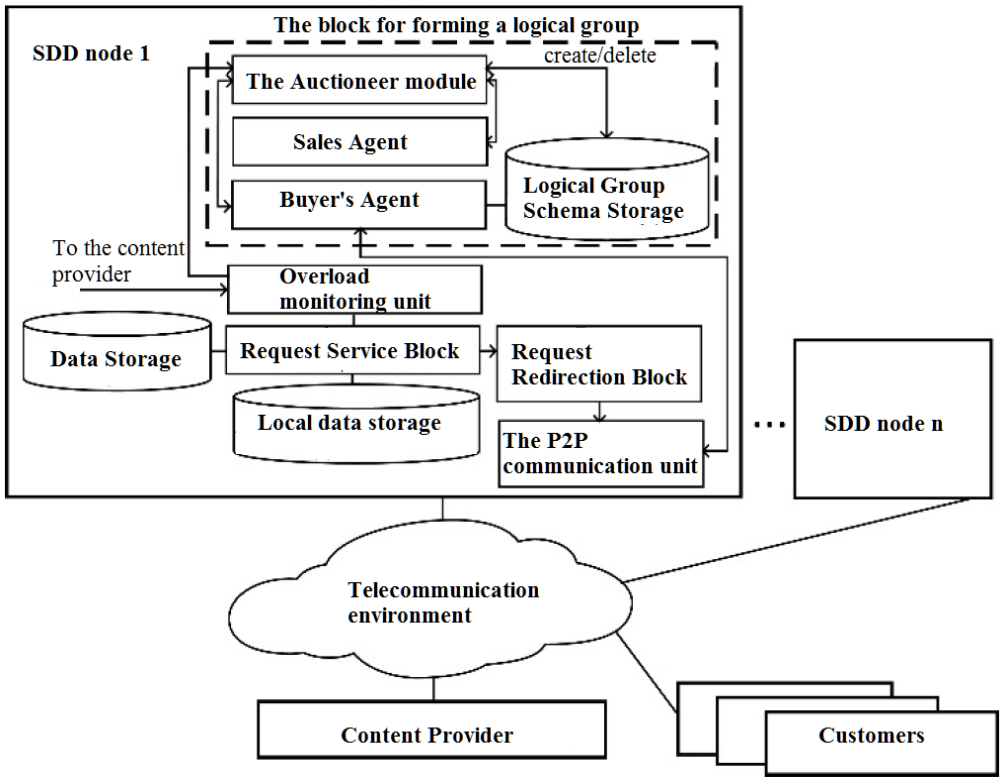

Figure 3. Architecture of a distributed DDS node with an overlay block for forming a logical node group

To assess the degree of achievement of the research goal, it was decided to conduct a simulation experiment based on the developed distributed DDS simulation model [14]. It is represented by a combined simulation environment, including: a simulator of the MiniNet network interaction environment, a simulator of the logical group formation unit in the AnyLogic environment, a simulator of the basic functions of the DDS node in the GPSS Studio environment.

An example of the average simulation results of a distributed DDS consisting of 2, 5, and 10 nodes, respectively, is shown in Figure 4. It can be seen that, regardless of the number of nodes in a distributed DDS, the DDS scheme with dynamic logical group formation implements a shorter response time for servicing requests.

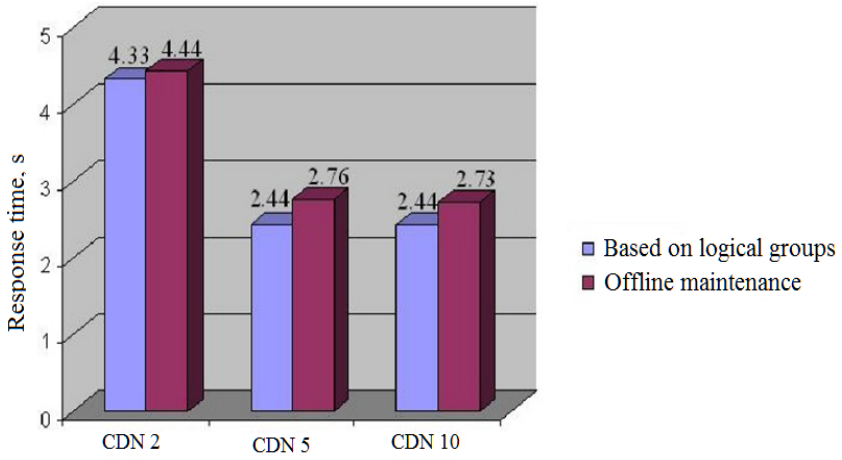

Figure 4. Results of a comparative simulation experiment for a distributed DDS with autonomous nodes and a logical group of nodes

5. CONCLUSION

The following main results were obtained:

1. A QS model of a multi-node distributed data delivery system has been developed, based on the principles of redistributing requests between multiple interacting data delivery nodes.

2. Algorithms have been developed for combining nodes of a distributed data delivery system and their mutual information coordination during the integration process.

3. The architecture of a multi-node distributed data delivery system based on an overlayable auction block for the formation of a logical group of nodes has been developed.

4. Experiments have been conducted to estimate the response time to high-intensity composite queries for the proposed architecture of a distributed data delivery system and the existing architecture based on the autonomous functioning of nodes. The experimental results show an increase of 3.5-4.2% (depending on the number of nodes in the logical group) in the responsiveness of servicing the test flow of composite requests (reducing the average response time of a node) by the architecture of a multi-node distributed data collection system developed (using the example of simulating a network of CND nodes) in comparison with servicing the specified flow by a set of autonomous nodes.

REFERENCES

[1] Zhuanhao W., Anirudh K., Hiren P. High Performance and Predictable Shared Last-level Cache for Safety-Critical Systems. *ACM Transactions on Embedded Computing Systems*, vol. 23, 2024. DOI: 10.1145/3687308.

[2] Teramura H., Ono K., Ando S., Yamazaki Y., Yamamoto S., Matsuo K. Experimental Facsimile Communication System on Packet Switched Data Network. *IEEE Transactions on Communications – TCOM*, vol. 29, 1981, pp. 1942-1951. DOI: 10.1109/TCOM.1981.1094945.

[3] Kumar D.H., Taori P., Mehtab A. *Demystifying Relational Database Management System*, 2022. Kripa Drishti publication, ISBN: 978-93-94570-09-2.

[4] Cintuglu M., Ishchenko D. Real Time Asynchronous Information Processing in Distributed Power Systems Control. *IEEE Transactions on Smart Grid*, vol. 13, no.1, 2021. pp.773-782. DOI: 10.1109/TSG.2021.3113174.

[5] Chaudhary R., Kumar R., Saxena N. A systematic review on federated learning system: a new paradigm to machine learning. *Knowledge and Information Systems*, vol. 67, no 2, 2024, pp. 1811-1914. DOI: 10.1007/s10115-024-02257-6.

[6] Shankar A. Multi-CDN Architecture: Enhancing content delivery resilience in high-traffic digital platforms. *World Journal of Advanced Engineering Technology and Sciences*, vol. 15, no. 2, 2025, pp.2084-2090. DOI: 10.30574/wjaets.2025.15.2.0745.

[7] Carrara G., Burle L., Medeiros D., Albuquerque C., Menezes D. Consistency, availability, and partition tolerance in blockchain: a survey on the consensus mechanism over peer-to-peer networking. *Annals of Telecommunications*, vol. 75, no. 2, 2020. DOI: 10.1007/s12243-020-00751-w.

[8] Forbes C., Evans M., Hastings N., Peacock B. Pareto Distribution. In: *Statistical Distributions*, Wiley, 2010. vol. 10.1002/9780470627242.ch34.

[9] Rego V. Some explicit formulas for mixed exponential service systems. *Computers and Operations Research*, vol. 15, no. 6, 1988, pp. 509-520. DOI: 10.1016/0305-0548(88)90047-0.

[10] Kravets O.Ja., Aksenov I.A., Rahman P.A., Atlasov I.V., Redkin Yu.V., Frantsisko O.Yu., Zaslavskaya O.Yu.. Operational control of probabilistic processes in a multi-stage specialized system. *International Journal on Information Technologies and Security*, vol. 15, no. 2, 2023, pp. 27-34.

11. Riska A., Diev V., Smirni E. Efficient fitting of long-tailed data sets into hyperexponential distributions. *Global Telecommunications Conference, 2002. GLOBECOM '02,* vol. 3, pp. 2513-2517 DOI: 10.1109/GLOCOM.2002.1189083.

12. Lin Y-F. A Generalized Laplace Transform Approximation for Nonlinear Groundwater Flow. Preprint. *Authorea*, 2025, April 14. DOI: 10.22541/au.174466155.50674543/v1.

[13] Schwartz J., Wen Q. A Subsidized Vickrey Auction for Cost Sharing. *Journal of Mathematical Economics*, vol. 77, 2007, pp. 32-38. DOI: 10.1016/j.jmateco.2018.06.002.

[14] Romansky R. Preliminary organization of virtual network based on program monitoring. *International Journal on Information Technologies and Security*, vol.16, no. 3, 2024, pp. 111-120.

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