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MODEL OF TRAFFIC ROUTING IN A HETEROGENEOUS DISTRIBUTED INFORMATION SYSTEM

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Abstract. *The article presents a mathematical model of finding the optimal route and its cost in the presence of various routing requirements in a heterogeneous information and communication network of an arbitrary unstable structure, allowing for max-imum efficient use of network resources, reducing the number of blockages and traffic delays. Theoretical researches were been confirmed by modeling traffic routing using the example of a fragment of a heterogeneous network.*

The purpose of the study: the search for optimal traffic routing algorithms. Re-search methods: analysis, mathematical modeling. Scientific novelty: the routing algorithms presented in the article for the first time. Practical value: the mathemat-ical model and algorithms may be used in real conditions of data traffic routing.

Key words: routing, traffic management, resource planning, management of information communications, distributed heterogeneous networks.

Introduction. The growing needs of practice require more and more computing resources, and their increasing complexity makes it necessary to consolidate a large number of heteroge-neous resources. The use of standard network technologies for these purposes does not lead directly to success, either because of the difficulties of access to such re-sources, and for technological reasons. A variant of the approach based on distribut-ed clusters (GRID) can be abstractly considered simply as a collection of computa-tional resources capable of solving computational problems. This approach works great if there are a lot of simple tasks and a lot of resources on which they run. An-other way to consider is a collection of objects that should be managed by running code as the only huge machine. Such an approach is good in homogeneous systems, or when administrative resources can be controlled. Therefore, to solve the problem, new approaches are required. In this research, it is assumed that you can use the main advantages of Grid - systems, abandoning the basic principle - separation of the user from the tools and launching applications through virtual organizations. On the contrary, the combination of the intermediate hardware-software and telecommuni-cations software such as Grid with a specific operating environment allows building distributed heterogeneous computing systems not only for running complex applica-tions, but also for optimizing them. In fact, it’s about building a specific type of mid-dleware PSE (problem solution environment), which allows to create a user-friendly operating environment that combines the advantages of the Grid toolkit with the capabilities for managing distributed computing resources (Fig. 1).

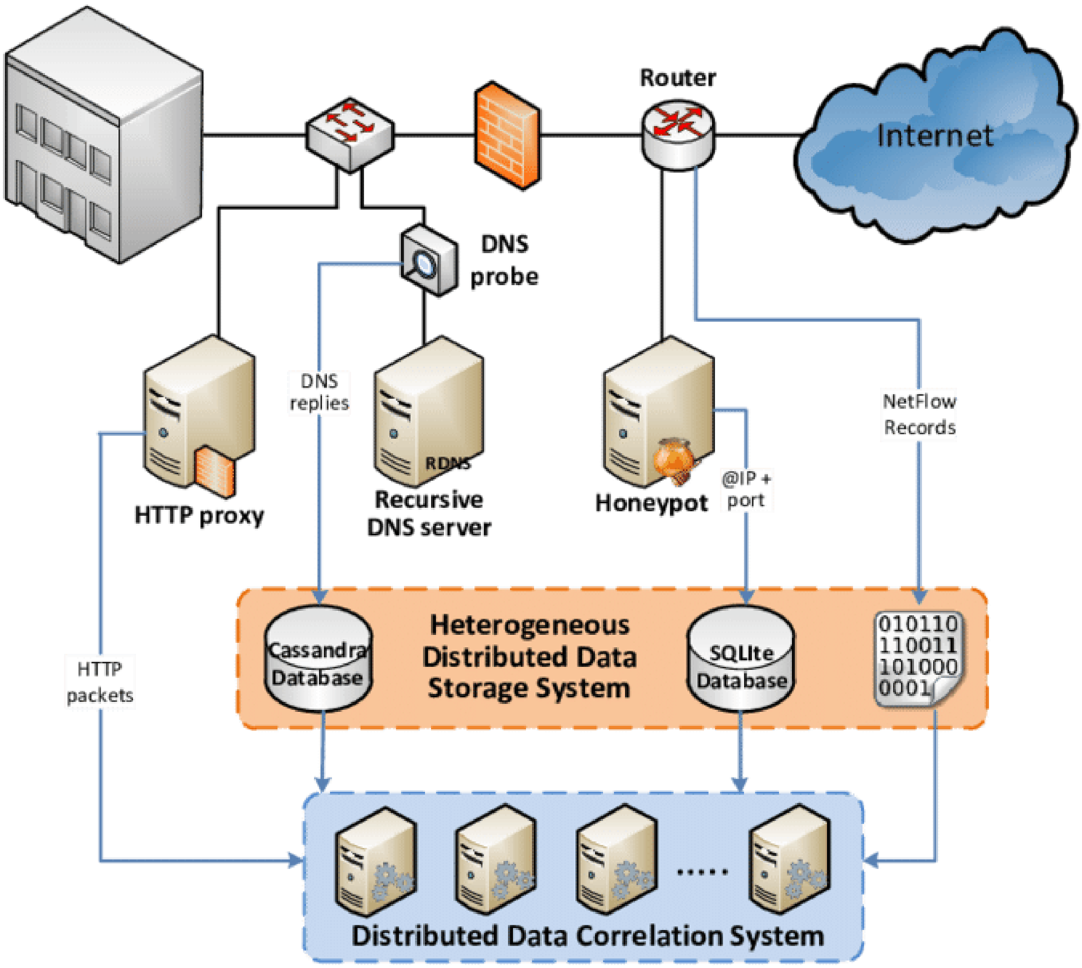

Figure 1. An example of a heterogeneous information and communication network

Any distributed information system primarily involves a network of nodes. There-fore, routing is one of the most important tasks in a distributed network. The efficien-cy of routing directly determines the performance of calculations as a whole, distrib-uted task scheduling, balancing and managing resources at run time, and the order of monitoring resources and tasks.

Setting a task for research. Currently, there are a large number of routing algorithms that satisfy the requirements for traffic transfer, quality of service parameters, service level agreements, etc. [1–5]. Moreover, almost all algorithms are designed for a stable network, do not take into account mobile nodes and heterogeneity of the structure. This article discusses a mathematical model of routing for modern heterogeneous information and communication networks with an unstable structure.

Thus, in this article, the authors propose to develop a methodology for creating and optimizing distributed heterogeneous computing systems based on routing. The basic idea is to combine three successive steps. First, with the help of specially select-ed software, the system integration of the computer systems included in the hetero-geneous complex is carried out. Then, on the basis of special routing algorithms, an operating environment is created for convenient user operation in a distributed com-puting environment. And, finally, on the basis of a set of simple mathematical mod-els, a synthetic test is built, which allows determining the performance of the created complex and, thus, carrying out its structural optimization. Establishes the adequacy of the results.

All values defined in this article are normalized and can be used for various dimensions and conditions: bandwidth and traffic volume are measured in convenient for a specific task units (bits, bytes, packets, etc.), the transmission cost determines some measure of transmission costs: transmission time, energy or economic costs of transmission, etc.

Mathematical model of routing. Consider a distributed information system (DIS) and the corresponding full directed graph $G = (V, E)$, where V is the set of nodes, E is the set of communication lines (routes) between each pair of nodes.

We define a set R, such that $R \subset V \times V$. Pairs of nodes from the set R correspond to pairs of network end nodes between which traffic is transmitted.

For $\forall(v_i, v_j) \in R$, define the set of all possible routes $Lij = \{l_1(v_i, v_j), l2(v_i, v_j), \dots, l_n(v_i, v_j)\}$ between nodes (v_i, v_j), where $l_r(v_i, v_j)$ - some unique route between nodes (v_i, v_j).

In [6], for each pair of nodes $(v_i, v_j) \in R$, the function $f(v_i, v_j) \geq 0$, was defined, describing the volume of traffic transferred between these nodes and the conditions for such a function without taking into account the weight fractions of the capacity of each individual route. Will define conditions satisfying the functions $f(v_i, v_j)$ taking into account the weight fractions of the carrying capacity of the route w:

$$F(p, v_i, v_j) = \sum_k f_{ij}(p, v_i, v_k) =$$

$$= \sum_k f_{ij}(p, v_k, v_j);\ \forall(v_k) \in \mathrm{V} \setminus \{v_i, v_j\} \quad (1)$$

$$F_{ij}(p, v_k, v_l) \leq \frac{w_{kl}}{w_{ij}} f(p, v_i, v_j) -$$

$$- \sum_{m,n} F_{mn}(p, v_k, v_l);\ (v_m, v_n) \in \mathrm{R} \setminus (v_i, v_j) \quad (2)$$

where $F_{ij}(v_k, v_l)$ is the fraction of traffic $F(v_i, v_j)$, flowing between nodes (v_k, v_l); $w_{kl} \geq 0$ is the route bandwidth between nodes (v_k, v_l), p is the data flow identifier.

Condition (1) determines that the volume of traffic transmitted over the network from node v_i will be equal to the volume of traffic entering node v_j. Condition (2) means that the amount of traffic transmitted by any route does not exceed the capacity of this route.

Consider the FIGURE as a graph, each pair of nodes (v_i, v_j) and the route between them (v_i, v_j) of which is assigned a tuple:

$$[w_{ij}, prob_{ij}, L_{ij}, f(v_i, v_j, t)] \quad (3)$$

where $prob_{ij}$ is the probability value of the existence of at least one route between nodes (v_i, v_j), $f(v_i, v_j, t) \geq 0$ is a function corresponding to the total volume of traffic transmitted between nodes (v_i, v_j) at each time t:

$$f(p, v_i, v_j, t) = \frac{dF(p, v_i, v_j)}{dt} \quad (4)$$

Each separate route $l_r \in L_{ij}$ corresponds to a tuple:

$$[w_r(v_i, v_j), prob_r(v_i, v_j), cost_r(v_i, v_j), f_r(p, v_i, v_j, t)];$$

$$0 \leq prob_r(v_i, v_j) \leq 1; \qquad 0 \leq cost_r(v_i, v_j) \quad (5)$$

where $prob_r(v_i, v_j)$ is the probability value for the existence of a route l_r between nodes (v_i, v_j), $cost_r(v_i, v_j)$ is the value of the cost of transmitting a conditional unit of information along the route l_r between nodes (v_i, v_j), $f_r((p, v_i, v_j, t) \geq 0$ is the function corresponding to the volume of traffic transmitted along the route l_r at each time t. We will also assume that the value of $prob_{ij}$, $prob_r(v_i, v_j)$ and $cost_r(v_i, v_j)$ are the same when transmitting traffic in both directions (i.e., the probability of the existence of a route and the cost of transmission along this route in the forward direction are equal to the probability of the existence of this route and the cost of transmission on the route in the opposite direction).

The probability of the existence of a route between two nodes of each unique route l_r is the probabilistic product of all intermediate routes (included in this route) between adjacent links on this route:

$$prob_r(v_i, v_j) =$$

$$= \prod_{m,n} prob_r(v_m, v_n);\ \forall l_r(v_m, v_n) \in l_r(v_i, v_j), \quad (6)$$

where r is the conditional number of the unique route between each pair of nodes (v_i, v_j). Hereinafter, we will consider only routes with a probability other than zero, since a route with a probability of zero can never realize itself.

The total probability of the existence of at least one route between a pair of nodes (v_i, v_j) is considered the probability sum of the probabilities of the existence of all unique routes between these nodes:

$$prob(v_i, v_j) = 1 - \\ - \prod_{\forall r} \left(1 - prob_r(v_i, v_j)\right); \ \forall l_r(v_i, v_j) \in L_{ij}, \tag{7.1}$$

$$prob(v_i, v_j) = 1 - \\ - \prod_{\forall r} (1 - \prod_{m,n} prob_r(v_m, v_n)); \\ \forall l_r(v_m, v_n) \in l_r(v_i, v_j) \in L_{ij}. \tag{7.2}$$

Formula (7.2) makes it possible to calculate the probability of the existence of at least one route between two nodes of a heterogeneous network, based on the probabilities of the existence of each individual fragment of the network.

The residual bandwidth of the l_r route section between intermediate nodes (v_m, v_n) is a value indicating by what value the data flow p^* can be increased along this route after deducting all third-party data streams:

$$w_r^*(p^*, v_m, v_n, t) = w_r(v_m, v_n) - \\ - \sum_{\forall g \in G} f_r(p, v_m, v_n, t), \forall p \in P \backslash p^* \tag{8}$$

where P is the set of data streams flowing along the l_r route. The residual bandwidth of the l_r route section between intermediate nodes (v_i, v_j) will correspond to the segment of the route with the lowest bandwidth:

$$w_r^*(p^*, v_i, v_j, t) = \min_{\forall (v_m, v_n)} (w_r^*(p^*, v_m, v_n, t)), \\ \forall (v_m, v_n) \in (v_m, v_n) \tag{8.1}$$

The amount of information transmitted in the stream p^* along the l_r route between a pair of nodes (v_i, v_j) during time T:

$$F_r(p^*, v_i, v_j) \leq \int_0^T w_r^*(p^*, v_i, v_j, t)\, dt \tag{9}$$

The cost of transferring a unit of information for a pair of nodes (v_i, v_j) for each unique route l_r will be considered the sum of the cost of transmitting a part of this data for each fragment of this route:

$$cost_r(v_i, v_j) = \\ = \sum_{m,n} cost_r(v_m, v_n) \frac{F_r(p^*, v_m, v_n)}{F_r(p^*, v_i, v_j)} \tag{10}$$

The relative cost of transmitting traffic for each unique route lr will be considered as the ratio of the cost of transmitting information on this route to the probability of the existence of this route:

$$cost_r^*(v_i, v_j) = \frac{cost_r(v_i, v_j)}{prob_r(v_i, v_j)}; \\ prob_r(v_i, v_j) > 0 \tag{11}$$

Obviously, the route with the lowest relative cost will be the most optimal route for transmitting information: such a route may have a higher cost than a route with a minimum cost, but the probabilistic losses in this route are much lower:

$$cost_o(v_i, v_j) = \min_r \left(cost_r^o(v_i, v_j)\right) = \\ = \min_r\left(\frac{cost_r(v_i, v_j)}{prob_r(v_i, v_j)}\right); \ prob_r(v_i, v_j) > 0, \tag{12}$$

where $cost_o$ is the cost of data transfer between nodes (v_i, v_j) along the most optimal route.

Modeling. Illustration of the method obtained with an example: the network (Fig. 2) receives a request to route traffic of size W from node A to node F. Consider the flow routing based on the routes:

least short way (shortest way);

the highest probability of the existence of the route (the most likely path);

the highest capacity of the route (the fastest way);

least cost data transfer.

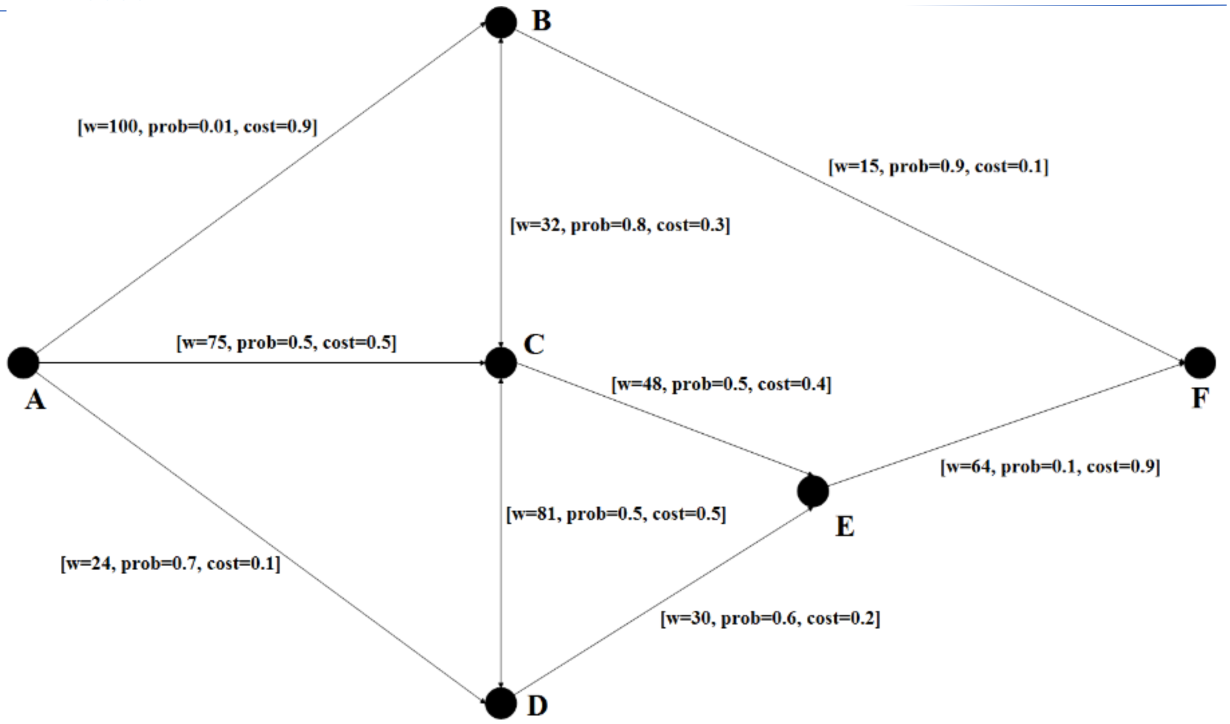

Figure 2. Model of a heterogeneous information and communication network

Given the heterogeneous and unstable nature of the network, we will imply the following:

each node has a memory - the information transmitted to the node is not lost even in the case of a temporary absence of a communication line. This is the main difference from routing methods in local area networks, where the route involves the establishment of a direct connection from the source to the receiver;

The capacity of a particular route segment cannot exceed the capacity of previous route segments, taking into account the probability of the existence of communication lines and the total line capacity. This requirement specifies that outgoing traffic at each node cannot exceed inbound.

In this article, the routing algorithms are not considered, therefore the routes for each individual routing model will be chosen empirically.

Routing the shortest path. For this routing model, the shortest route is the route through the ABF nodes.

For fragment AB, the relative throughput (taking into account the probability of the existence of a route) will be equal to:

$$w^*(v_A, v_B) = w(v_A, v_B) * prob(v_A, v_B) =$$

$$= 100 * 0.01 = 1,$$

cost of traffic transfer volume W:

$$COST(v_A, v_B) = \frac{W * cost(v_A, v_B)}{w^*(v_A, v_B)} = \frac{W * 0.9}{1} =$$
$$= 0.9\,W.$$

For a BF fragment, the relative throughput (taking into account the probability of the existence of a route) and the throughput of previous sections of the route will be equal to:

$$w^*(v_B, v_F) =$$

$$= \min\big(w(v_B, v_F) * prob(v_B, v_F), w^*(v_A, v_B)\big)$$
$$= 1,$$

cost of traffic transfer volume W:

$$COST(v_B, v_F) = \frac{W * cost(v_B, v_F)}{w^*(v_B, v_F)} = 0.1\,W.$$

The total cost of traffic on the route ABF will be equal to:

$$COST(v_A, v_F) = COST(v_A, v_B) +$$

$$+ COST(v_B, v_F) = W.$$

Routing along the most probable path. For a given routing model, we determine the probabilities of the existence of each of the routes:

Table 1. Routing along the most probable path

ABF	*ABCEF*	*ABCDEF*	*ACBF*	*ACEF*
0.009	0.0004	0.00024	0.36	0.025
ACDEF	ADCBF	ADCEF	ADEF	ADECBF
0.015	0.252	0.0175	0.042	0.1512

From the results obtained (Table 1), it is clear that the route is most likely to have ACBF.

For each route fragment, we calculate the relative throughput and cost of transmitting traffic of volume W for fragments of the AC, CB, BF route:

$$w^*(v_A, v_c) = w(v_A, v_c) * prob(v_A, v_c) = 37.5,$$

$$COST(v_A, v_c) = \frac{W * cost(v_A, v_c)}{w^*(v_A, v_c)} = 0.013\, W.$$

$$w^*(v_C, v_B) =$$

$$= \min\big(w(v_C, v_B) * prob(v_C, v_B), w^*(v_A, v_C)\big) = 25.6,$$

$$COST(v_C, v_B) = \frac{W * cost(v_C, v_B)}{w^*(v_C, v_B)} = 0.012\, W.$$

$$w^*(v_B, v_F) =$$

$$= \min\big(w(v_B, v_F) * prob(v_B, v_F), w^*(v_A, v_B)\big) = 13.5,$$

$$COST(v_B, v_F) = \frac{W * cost(v_B, v_F)}{w^*(v_B, v_F)} = 0.007\, W.$$

The total cost of traffic on the ACBF route will be equal to:

$$COST(v_A, v_F) = COST(v_A, v_c) + COST(v_C, v_B) + COST(v_B, v_F) = 0.032\, W.$$

The route with the highest bandwidth. For this routing model, we determine the relative throughput for each network fragment (Fig. 3):

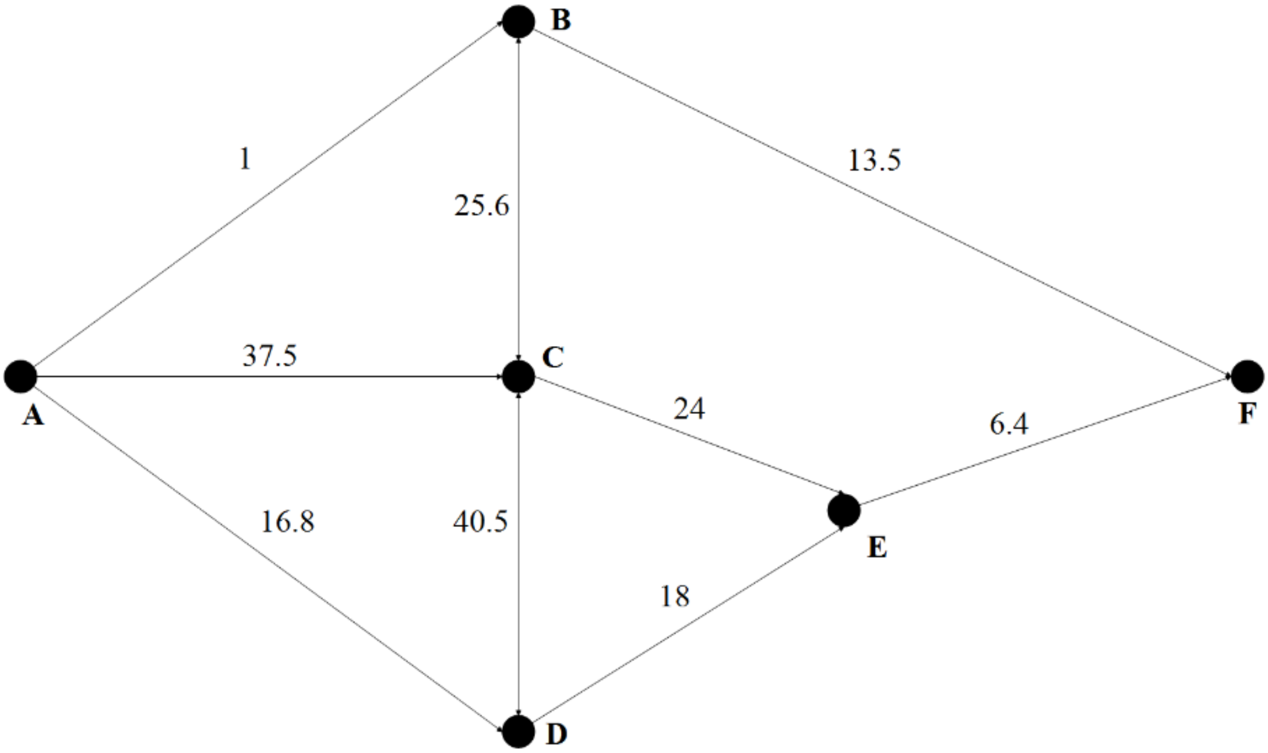

Figure 3. Relative bandwidth of communication lines

determine the probabilities of the existence of each of the routes:

Table 2. The route with the highest bandwidth

ABF	ABCEF	ABCDEF	ACBF	ACEF
1	1	1	13.5	6.4
ACDEF	ADCBF	ADCEF	ADEF	ADECBF
6.4	13.5	6.4	6.4	6.4

According to the results obtained (Table 2), it is clear that the routes with the highest throughput are: ACBF and ADCBF.

The total cost of transmission for the ACBF route was calculated in the previous model (the route along the most probable route):

$$COST(v_A, v_F) = COST(v_A, v_c) + COST(v_C, v_B)$$
$$+COST(v_B, v_F) = 0.032\,W.$$

The total cost of traffic on the route ADCBF will be equal to:

$$COST(v_A, v_F) = COST(v_A, v_D) + COST(v_D, v_C)$$
$$+ COST(v_C, v_B) + COST(v_B, v_F) = 0.061\,W.$$

The route with the lowest cost. For a given route, the relative cost of transmitting traffic of volume W over any data line will be equal to:

$$COST = \frac{W * cost}{w * prob} = \frac{W * cost^*}{w} = \frac{W}{w^*} * cost.$$

We calculate the cost of data transfer and the relative bandwidth by sifting out the “extra” branches by parsing the network into triangles and eliminating the branches inside each triangle (outgoing point and a pair of points with direct connection) starting from point A.

Iteration 1: a pair of points (B, C), a triangle (A, B, C):

$$w_{AB}^* = w(v_A, v_B) * prob(v_A, v_B) = 1,$$

$$w_{AC}^* = w(v_A, v_C) * prob(v_A, v_C) = 37.5,$$

$$w_{ABC}^* = \min(w(v_B, v_C) * prob(v_B, v_C), w_{AB}^*) = 1,$$

$$w_{ACB}^* = \min(w(v_C, v_B) * prob(v_C, v_B), w_{AC}^*) = 25.6,$$

$$COST_{AB} = \frac{W * cost(v_A, v_B)}{w_{AB}^*} = 0.9\,W,$$

$$COST_{AC} = \frac{W * cost(v_A, v_C)}{w_{AC}^*} = 0.013\,W,$$

$$COST_{ABC} = COST_{AB} + \frac{W * cost(v_B, v_C)}{w_{ABC}^*} = 1.2\,W.$$

$$COST_{ACB} = COST_{AC} + \frac{W * cost(v_B, v_C)}{w_{ACB}^*} = 0.024\,W.$$

From the calculated values, it can be seen that the ACB transmission (0.024W) is lower than the AB route (0.9W) and the AC transmission (0.013W) is lower than the ABC route (1.2W). Consequently, the AB communication line should be excluded from further calculations.

Iteration 2: a pair of points (C, D), a triangle (A, C, D):

$$w_{AD}^* = w(v_A, v_D) * prob(v_A, v_D) = 16.8,$$

$$w_{ADC}^* = \min(w(v_C, v_D) * prob(v_C, v_D), w_{AD}^*) = 16.8,$$

$$w_{ACD}^* = \min(w(v_C, v_D) * prob(v_C, v_D), w_{AC}^*) = 37.5,$$

$$COST_{AD} = \frac{W * cost(v_A, v_D)}{w_{AD}^*} = 0.006\,W,$$

$$COST_{ADC} = COST_{AD} + \frac{W * cost(v_D, v_C)}{w_{ADC}^*} = 0.036\,W.$$

$$COST_{ACD} = COST_{AC} + \frac{W * cost(v_D, v_C)}{w^*_{ACD}} = 0.026\, W.$$

From the calculated values, it can be seen that the ACD (0.026W) transmission is higher than the AD route (0.006W) and the AC transmission (0.013W) is lower than the ADC transmission (0.026W). Therefore, the CD line should be excluded from further calculations.

After the first two iterations, the network will look like in Fig. 4. In this case, the lines AD and DE can be combined into one line AE with parameters:

$$prob_{AE} = \min(prob_{AD}, prob_{DE}) = 0.6,$$

$$w_{AE} = \min(w_{AD}, w_{DE}) = 24,$$

$$cost_{AE} = cost_{AD} * prob_{DE} + cost_{DE} * prob_{AD} = 0.2.$$

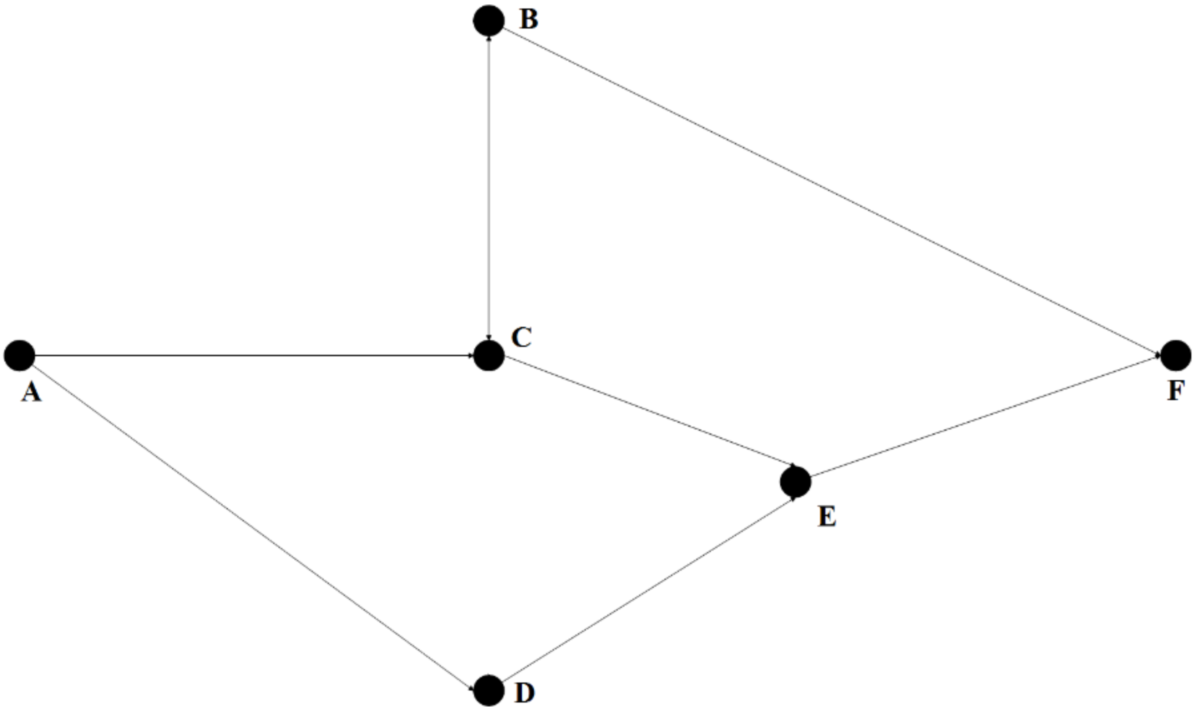

Figure 4. Network status after the first two iterations

Iteration 3: a pair of points (C, E), a triangle (A, C, E):

$$w^*_{AE} = w(v_A, v_E) * prob(v_A, v_E) = 14.4,$$

$$w^*_{AEC} = \min(w(v_C, v_E) * prob(v_C, v_E), w^*_{AE}) = 14.4,$$

$$w^*_{ACE} = \min(w(v_C, v_E) * prob(v_C, v_E), w^*_{AC}) = 24,$$

$$COST_{AE} = \frac{W * cost(v_A, v_E)}{w^*_{AE}} = 0.014\, W,$$

$$COST_{AEC} = COST_{AE} + \frac{W * cost(v_E, v_C)}{w^*_{AEC}} = 0.042\, W.$$

$$COST_{ACE} = COST_{AC} + \frac{W * cost(v_E, v_C)}{w^*_{ACE}} = 0.030\, W.$$

From the calculated values, it can be seen that the ACE (0.030W) transmission is higher than the AE route (0.014W) and the AC transmission (0.013W) is lower than the AEC route (0.042W). Therefore, the CE link should be excluded from further calculations.

After the third iteration, only two direct routes remain: ACBF and ADEF. Calculate the relative bandwidth and cost for each of them:

$$w^*_{ACBF} = \min(w(v_B, v_F) * prob(v_B, v_F), w^*_{ACB}) = 13.05,$$

$$w^*_{ADEF} = \min(w(v_E, v_F) * prob(v_E, v_F), w^*_{ADE}) = 6.4,$$

$$COST_{ACBF} = COST_{ACB} + \frac{W * cost(v_B, v_F)}{w^*_{ACBF}} = 0.032\,W.$$

$$COST_{ADEF} = COST_{ADE} + \frac{W * cost(v_E, v_F)}{w^*_{ADEF}} = 0.155\,W.$$

The results show that the best route will be the ACBF route with a cost of 0.032W. These results are consistent with the results when finding routes with the highest throughput and the highest probability of the existence of routes. At the same time, using the model of building a route at the lowest cost allows you to avoid collecting statistical information of the entire network and rely on information only about neighboring nodes.

Evaluation of the adequacy of the results. The reliability of these results and conclusions is confirmed by the results of testing algorithms and software, as well as the practical use of the developed algorithmic and software methods and tools. These studies were conducted by the method of statistical tests.

To assess the adequacy (reliability) of the approximation, the following relationship was used [9-10]:

$$R^2 = 1 - \frac{\sum_i (Y_i - \hat{Y}_i)^2}{(\sum_i Y_i^2) - (\sum_i Y_i)^2 \big/ n},$$

where R^2 is the coefficient of determination;

$Y_i, \hat{Y}_i$ - experimental data and approximating values of dependence, respectively;

n – the number of points of approximation.

Based on experimental data, a confidence interval was calculated to determine the extremum for each species. For a normal distribution [9, 10], according to the "three sigma" rule, the confidence interval with a probability of 95% is defined as:

$$\beta = \pm(\Delta \approx 2\sigma)\ ,$$

where β - estimated value (maximum traffic in the system),%;

Δ - accuracy of assessment,%;

σ - standard deviation,%.

The value is also estimated using the confidence interval for the general variance:

$$\frac{nS^2}{\chi^2_{n-1}\left(\frac{\alpha}{2}\right)} < \sigma^2 < \frac{nS^2}{\chi^2_{n-1}\left(1-\frac{\alpha}{2}\right)},$$

where α - the level of significance used to calculate the level of reliability of a given distribution;

χ^2_{n-1} - the value of the Pearson distribution function (χ^2-distribution) with the number of degrees of freedom (n-1);

S^2 - unbiased estimate of the standard deviation of the total population.

From where the limiting value of the error for the calculated value will be

$$\Delta \approx 2\sigma = 2\sqrt{\frac{nS^2}{\chi^2_{n-1}\left(1-\frac{\alpha}{2}\right)}}$$

The traditional criterion used in such cases is the mean square error of MSE prediction (Mean Square Error, that is, the quadratic norm [9]) or the estimate of the normalized mean error of generalization NMSE (Normalized Mean Squared Error [10]).

The evaluation of the model adequacy indicators showed [11] fairly good values for a number of key indicators. So, according to the coefficient of determination, modeling showed results at the level of R^2=0,72-0,74. The estimation of the normalized mean error of generalization NMSE to 0,0015. The level of reliability while 95%. All this confirms the adequacy of the resulting model and the modeling process as a whole.

Conclusions

1. The paper discusses the main problems encountered in the integration of heterogeneous distributed computing resources. The advantages and disadvantages of integrating distributed computing resources at the system level are analyzed.

2. Solved the problem of finding the optimal route for traffic transmission, taking into account the load on the network, the residual bandwidth of its links and routing requirements, subject to variable network structure, the cost of traffic transmission and the possibility of its separation.

3. The proposed mathematical model can be applied to develop methods and routing algorithms, search for solutions to the problem of

routing in information and communication networks of complex structure. The model is implemented by splitting the network graph into components, for each of which the described routing model is applied, followed by the composition of a common solution.

4. The resulting mathematical model of traffic routing in a heterogeneous distributed information system is fully adequate (coefficient of determination R^2=0,72-0,74, normalized average error NMSE to 0.0015 with a level of reliability of 95%).

References

1. Capone A., Fratta L., Martignon F. Dynamic online QoS routing schemes: performance and bounds // Computer Networks. 2006. N 50. P. 966—981.
2. Capone A., Fratta L., Martignon F. Dynamic routing of bandwidth guaran-teed connections in MPLS networks // Intern. Journal on Wireless & Optical Commu-nications. 2003. N 1. P. 75—86
3. Kwong Kin-Wah, Guerin R., Shakh A., Shu Tao. Balancing performance, ro-bustness and flexibility in routing systems // Proc. of ACM CoNEXT. Madrid, 2008. P. 372—383.
4. Hadjiona M., Georgiou C., Papa M., Vassiliou V. A hybrid fault-tolerant al-gorithm for MPLS networks // Proc. of WWIC. Tampere. 2008. P. 41—52.
5. Efremov A.S., Zelentsov V.A., Mironov A.S., Ulasen S.N. Forecasting the residual life of communication equipment // Vestn. communication 2004. No. 4. P. 93—99.
6. Zelentsov V. A., Tsivirko E. G., Chukarin A. V. Method of traffic routing in the information-communication heterogeneous network // Izvestia Higher. educational institutions. 2010. No. 11. Vol. 53. P. 56-61.
7. Berezko M. P., Vishnevsky V. M., Levner E. V., Fedotov E. V. Mathematical models for the study of routing algorithms in data networks // Informational processes. 2001. V. 1, No. 2. S. 103-125.
8. Bogdanov AV, Mo Tun Development of distributed computing systems and launching applications in a heterogeneous computing environment http://tekhnosfera.com/razrabotka-raspredelennyh-geterogennyh-vychislitelnyh-sistem-i-zapusk-prilozheniy-v-raspredelennoy-vychislitelnoy -srede.
9. Denisov A.A. The theory of large control systems / A.A. Denisov, D.N. Kolesnikov.– L .: Energoizdat, Leningr. Separation, 1982.– 287 p.
10. Molchanov A.A. Modeling and design of complex systems / Molchanov A.A. - K .: High School, 1988.– 359 p.
11. Kupin A.I., Poddubny B.A., Muzyka I.O. Mathematical model of traffic routing in a heterogeneous information environment // Systems Technologies. Regional mizhvuzivsky zbirnik naukovih prats. - Vip. 2 (109) .- Dnipro, 2017.- P.14-19.