The Algorithm and Software for Selection of Optimal Topology of Information Systems with Limited Budget

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Abstract

In the context of rapid advances in information technology, there is an increasing demand for the development of efficient, scalable, and resilient network infrastructures that integrate distributed computing modules or autonomous devices into a cohesive system. Such a need is particularly pronounced in fields that require high levels of automation, fault tolerance, and adaptability — including telecommunications, cloud computing, decision support systems, healthcare information networks, banking infrastructure, and next-generation energy grids. When the availability of financial and physical resources is limited, a major challenge arises: not only must the network successfully interconnect all its components, but it must also guarantee maximum functional stability under a constrained total budget and varying costs for establishing individual communication links.

This paper proposes a novel method for constructing an optimal node connection topology represented as an undirected graph, with a specific focus on maximizing the network's robustness under cost constraints. The proposed model formalizes functional stability using a functional stability indicator. An optimization algorithm is developed to identify the most resilient network configuration — one that minimizes the risk of fragmentation or failure due to the loss of specific links or nodes. A key component of the model is the integration of edge weights representing individual link costs, alongside a global budget constraint enforced as part of the optimization objective.

Furthermore, the study introduces a software prototype that implements the developed algorithm. The tool provides an automated mechanism for generating optimal network topologies, alongside features for visualizing the resulting structure. The results presented in this work may be directly applied in the design and deployment of intelligent distributed systems that demand high resilience and adaptability, ensuring robust performance in real-world operational environments.

Keywords

Optimization, computer network, functional stability, distributed systems, topology.

1. Introduction

The use of various networks is a popular approach for solving tasks in many fields [1-3]. However, to utilize these networks effectively, it is necessary to establish connections between

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multiple machines (modules, sub-networks, etc.). Naturally, real-world tasks require considering various factors such as connection time, cost, and other constraints. Given the need for highly reliable networks while adhering to budget limitations, it would be beneficial to have an algorithm that generates an optimal connection topology – one that maximizes functional stability [4-6] while staying within a given budget.

This problem can be formulated as a graph enumeration or traversal task [4, 5, 7]. However, many existing graph-based algorithms either provide only partial solutions to this problem or require excessive computation time. This work proposes a new modification of an exhaustive graph search algorithm that fully addresses the described problem while significantly reducing the required computation time.

2. An algorithm description and analysis

Optimization of exhaustive graph, described in this work based on two concepts: decreasing of number of traversed graphs an estimation of indicator of functional stability. After description of the algorithm it would be good to see how this algorithm works, For automation of this algorithm authors developed software, what allows to visualize optimal topology of resulting network. Using developed software it will be shown, that described algorithm may give good optimization of finding of topology of connections of machines between each other.

2.1. Description of a selection algorithm

Let consider, that we have n machines and we want to connect it between each other by connection lines. In other hand, let consider, that we know general budget B and we have prizes matrix

$$C = \left\| c_{ij} \right\|_{i,j=1,2,\dots,n},$$

where c_{ij} is a cost of laying a communication line between machines v_i and v_j. For estimation of functional stability of considered information let use indicator $\bar{R}$ [4], what may be defined as integral

$$\bar{R} = \min_{\substack{i,j=1,2,\dots,n \\ i \neq j}} \int_0^1 R_{ij}(p)\,dp, \tag{1}$$

where $R_{ij}(p) = R_{ij}$ is probability of connectivity [4] for pair of vertices (v_i, v_j) in case, when probability of serviceability of all machines and connection lines equals 1 or p.

As we know, selection of topology of the metwork, what is optimal in some sense [8, 9], is equivalent to the task of selection of (mostly, unordered) graph $G = G(V, L)$, what describes a topology of information system, with number of vertices equals the number of machines. If we have criterion of optimality, we may use exhaustive search of graphs to search optimal. But exhaustive search of graphs in case of graph with n vertices have computational difficulty equals $O\left(2^{\frac{n(n-1)}{2}}\right)$, what is very bad variant. This factor is a reason to optimization of exhaustive search of graphs.

For optimization of exhaustive search of graphs with n vertices let use two ideas. First idea based on limitation of number of connection lines. To do it let consider sequences: first sequence (let note it as $\left\{\bar{\lambda}_u\right\}$) is a sequence of values $c_{ij}, i = 2,3,\dots,n, j = 1,2,\dots,i-1$, what are sorted in descending order and second sequence (let note it as $\left\{\bar{\bar{\lambda}}_u\right\}$) is a sequence of values $c_{ij}, i = 2,3,\dots,n, j = 1,2,\dots,i-1$, what are sorted in ascending order. Now let consider numbers $\bar{N}$ and $\bar{\bar{N}}$, what may be calculated by formulas

$$\bar{N} = \max\left\{n : n \in \mathbb{N} \wedge \sum_{u=1}^{n} \bar{\lambda}_u \le B\right\},$$
$$\bar{\bar{N}} = \max\left\{n : n \in \mathbb{N} \wedge \sum_{u=1}^{n} \bar{\bar{\lambda}}_u \le B\right\}.$$

Using purpose, that there is a sense to work only with connected graphs, and numbers $\bar{N}$, $\bar{\bar{N}}$, we may formulate interval of permissible number of communication lines formula

$$\max\left(n-1, \min\left(\bar{N}, \bar{\bar{N}}\right)\right) \le |L| \le \min\left(\frac{n(n-1)}{2}, \max\left(\bar{N}, \bar{\bar{N}}\right)\right), \tag{2}$$

Second idea of optimization based on approximation of indicator $\bar{R}$ using regression polynomial $\tilde{P}_3$, what is described in [4] and may be written by formula

$$\bar{R} \approx \tilde{P}_3 = \tilde{P}_3\left(\eta_{\min}, \eta_{\max}, S, q_G, u_G\right) =$$
$$= 7{,}01\eta_{\min} + 2{,}57\eta_{\max} + 1{,}14S - 13{,}69q_G - 3{,}84u_G - 14\eta_{\min}^2 - 4{,}56\eta_{\min}\eta_{\max} + 5{,}6\eta_{\min}S -$$
$$-21{,}83\eta_{\min}q_G + 7{,}54\eta_{\min}u_G - 1{,}63\eta_{\max}^2 - 2{,}11\eta_{\max}S - 6{,}53\eta_{\max}q_G + 7{,}05\eta_{\max}u_G - 7{,}96S^2 +$$

$$+32{,}52Sq_G + 0{,}19Su_G + 35{,}09q_G^2 + 4{,}38q_Gu_G - 2{,}89u_G^2 + 12{,}98\eta_{\min}^3 - 1{,}66\eta_{\min}^2\eta_{\max} - 7{,}23\eta_{\min}^2S +$$
$$+12{,}31\eta_{\min}^2q_G + 4{,}42\eta_{\min}^2u_G + 0{,}72\eta_{\min}\eta_{\max}^2 + 7{,}89\eta_{\min}\eta_{\max}S + 4{,}66\eta_{\min}\eta_{\max}q_G - 1{,}74\eta_{\min}\eta_{\max}u_G -$$
$$-7{,}23\eta_{\min}S^2 + 17{,}93\eta_{\min}Sq_G - 13{,}87\eta_{\min}Su_G + 6{,}99\eta_{\min}q_G^2 - 4{,}48\eta_{\min}q_Gu_G - 0{,}28\eta_{\min}u_G^2 -$$
$$-0{,}49\eta_{\max}^3 + 5{,}21\eta_{\max}^2S + 3{,}09\eta_{\max}^2q_G - 4{,}03\eta_{\max}^2u_G - 5{,}78\eta_{\max}S^2 - 5{,}6\eta_{\max}Sq_G -$$
$$-7{,}64\eta_{\max}Su_G + 5{,}09\eta_{\max}q_G^2 + 3{,}35\eta_{\max}q_Gu_G + 7{,}19\eta_{\max}u_G^2 + 7{,}22S^3 - 1{,}48S^2q_G +$$
$$+13{,}25S^2u_G - 50{,}9Sq_G^2 - 20{,}74Sq_Gu_G + 0{,}49Su_G^2 - 24{,}57q_G^3 + 11{,}39q_G^2u_G + 0{,}47q_Gu_G^2 - 3{,}7u_G^3, \tag{3}$$

where $\eta_{\min} = \frac{d_{\min}}{n-1}$, $\eta_{\max} = \frac{d_{\max}}{n-1}$,, $q_G = \frac{\kappa_G}{n-1}$, $u_G = \frac{\lambda_G}{n-1}$,, $d_{\min}$ is min degree of a graph G, $d_{\max}$ is max degree of a graph G, κ_G is a degree of vertex connectivity of graph G, λ_G is degree of edge connectivity and n is a number of vertices (what represent machines). Using (2) and (3) we may optimize search of optimal topology of considered information system, what is described by unordered connected graph G or, in other words, we will be able to answer, how to connect n machines using conditions, described above.

2.2. Examples of usage of described algorithm using its realization in software

In borders of the study a specialized software was realized. This software realizes described algorithm for finding optimal way of connection of machines in one information system. To see its work, let consider two examples.

2.2.1. First example of usage of described algorithm

Let purpose, that it's needed to connect four servers between each other and we know, that general budget, what is given for connection, equals 10000$ and prizes for laying every connection line may be represented by matrix

$$C = \begin{pmatrix} 0 & 3250 & 2250 & 999 \\ 3250 & 0 & 3750 & 5600 \\ 2250 & 3750 & 0 & 2000 \\ 999 & 5600 & 2000 & 0 \end{pmatrix}.$$

If we enter these data into the realized software, we will have result like demonstrated on fig. 1.

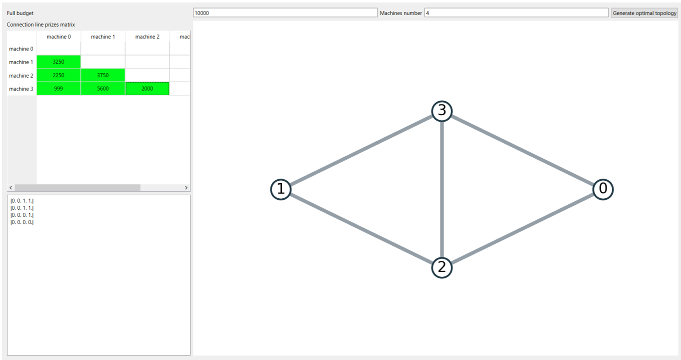

Figure 1: Output of realized software for first example

As we may see on fig. 1, if we numerate servers using numbers from 0 to 3, the most functionally stable variant of connection, based on given budget, may be demonstrated by built graph.

2.2.2. Second example of usage of described algorithm

Now let purpose, that it's needed to connect five servers between each other and we know, that general budget, what is given for connection, equals 10000$ again, but and prizes for laying every connection line may be represented by matrix

$$C = \begin{pmatrix} 0 & 1500 & 2400 & 3100 & 2210 \\ 1500 & 0 & 1750 & 1900 & 4300 \\ 2400 & 1750 & 0 & 1450 & 2250 \\ 3100 & 1900 & 1450 & 0 & 3250 \\ 2210 & 4300 & 2250 & 3250 & 0 \end{pmatrix}.$$

If we enter these data into the realized software, we will have result like demonstrated on fig. 2.

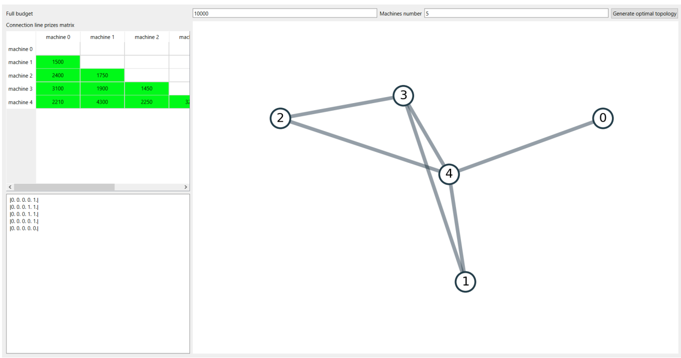

Figure 2: Output of realized software for second example

As we see on fig. 2, topology of given network is not very functionally stable, but more functionally stable will be too valuable.

2.3. Analysis of demonstrated examples

Let compare a number of graphs, what was traversed in the process finding of optimal topology. To do it let use table 1.

Table 1
Number of traversed graphs in described examples

Example	In exhaustive search, number of graphs	In described algorithm, numbers of graphs
First	64	41
Second	1024	672

As we see on table 1, described method may decrease a number of traversed graphs more, than 30%. It gives excellent optimization in finding of optimal topology of connections of servers. But it would be interesting to see, for what number of graphs we need do calculate an indicator of functional stability (1).

Table 2
Number of traversed graphs in described examples, for which indicator (1) was calculated

Example	In exhaustive search, number of graphs	In described algorithm, numbers of graphs
First	64	41
Second	1024	672

As we see on table 2, condition (2) may guarantee, that for all graphs with allowed number of connection lines we will estimate indicator of functional stability (1). In other hand, this factor combined with (3) allows to economy a time for comparison in selection of optimal topology. All this guarantees decreasing of general time, needed for selection of optimal calculations.

3. Conclusions

This work demonstrates optimized algorithm of finding of topology of network, optimal in sense of functional stability, considering fixed maximum budget for connection of machines. As examples and additional analysis shows, described algorithm allows to have excellent optimization in context of different parameters of difficulty of calculations.

These results may be used in various fields, for example, in IoT [9, 10], data transmission [11-13] and processing [14-17], development different systems [18-20], etc.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] V. Petrivskyi, O. Bychkov, V. Shevchenko, V. Martsenyuk, and M. Bernas, “A method for maximum coverage of the territory by sensors with minimization of cost and assessment of survivability,” Appl. Sci., vol. 12, no. 6, p. 3059, 2022. DOI: 10.3390/app12063059.

[2] V. Pichkur, V. Sobchuk, O. Laptiev, D. Cherniy, V. Matvienko, and J. Fedorenko, “The adaptive correction of angular velocities of an unmanned aerial vehicle based on discrete measurements of orientation,” in Proc. IEEE 7th Int. Conf. Methods Syst. Navigation Motion Control (MSNMC), 2023, pp. 91–95. DOI: 10.1109/MSNMC61017.2023.10329226.

[3] O. Barabash, V. Sobchuk, A. Sobchuk, A. Musienko, and O. Laptiev, “Algorithms for synthesis of functionally stable wireless sensor network,” Adv. Inf. Syst., vol. 9, no. 1, pp. 70–79, 2025. DOI: 10.20998/2522-9052.2025.1.08.

[4] O. Barabash and A. Makarchuk, “Development of a new indicator of functional reliability and its evaluation using multivariable polynomial regression,” Adv. Inf. Technol., vol. 1, no. 3, pp. 59–66, 2024.
[5] O. Barabash, A. Makarchuk, A. Musienko, and O. Maistrov, “Prediction of fulfilling the conditions of functional reliability of information systems using machine learning models,” in Proc. IEEE 7th Int. Conf. Actual Problems Unmanned Aerial Vehicles Dev. (APUAVD), 2024, pp. 179–182. DOI: 10.1109/APUAVD64488.2024.10765875.
[6] Y. Syvytsky and V. Shevchenko, “Simulation model of information system transformation to increase survivability against cyber threats,” CEUR Workshop Proc., vol. 3826, pp. 319–325, 2024.
[7] V. Petrivskyi, V. Shevchenko, S. Yevseiev, O. Milov, O. Laptiev, O. Bychkov, V. Fedoriienko, M. Tkachenko, O. Kurchenko, I. Opirskyy, “Development of a modification of the method for constructing energy-efficient sensor networks using static and dynamic sensors,” East.-Eur. J. Enterp. Technol., vol. 1, no. 9(115), pp. 15–23, 2022. DOI: 10.15587/1729-4061.2022.252988.
[8] A. Y. Mishchuk and A. M. Shutovskyi, “Optimization properties of generalized Chebyshev–Poisson integrals,” Cybern. Syst. Anal., vol. 60, no. 4, pp. 613–620, 2024. DOI: 10.1007/s10559-024-00700-8.
[9] N. Kuchuk, S. Kashkevich, V. Radchenko, Y. Andrusenko, and H. Kuchuk, “Applying edge computing in the execution IoT operative transactions,” Adv. Inf. Syst., vol. 8, no. 4, pp. 49–59, 2024. DOI: 10.20998/2522-9052.2024.4.07.
[10] M. Guissi, M. H. El Yousfi Alaoui, L. Belarbi, and A. Chaik, “IoT for predictive maintenance of critical medical equipment in a hospital structure,” Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, vol. 14, no. 2, pp. 71–76, 2024. DOI: 10.35784/iapgos.6057.
[11] O. Laptiev V. Sobchuk, A. Ryzhov, A. Sobchuk, S. Kopytko, G. Shuklin, “Harmonic operators in mathematical models of sources of detection of unauthorized access to information,” in Proc. HORA 2024 - 6th Int. Congr. Human-Comput. Interact., Optimization, Robotic Appl., 2024. DOI: 10.1109/HORA61326.2024.10550552.
[12] O. Laptiev A. Sobchuk, A. Ryzhov, O. Perehuda, I. Tsygansvska, S. Kopytko, “Applied aspects of polyharmonic functions for security and reliability of data transmission,” in Proc. ISMSIT 2024 - 8th Int. Symp. Multidiscip. Stud. Innov. Technol., 2024. DOI: 10.1109/ISMSIT63511.2024.10757187.
[13] A. Makarchuk, I. Kal'chuk, Y. Kharkevych, and G. Kharkevych, “Application of trigonometric interpolation polynomials to signal processing,” in Proc. IEEE 4th Int. Conf. Adv. Trends Inf. Theory (ATIT), 2022. DOI: 10.1109/ATIT58178.2022.10024182.
[14] S. Herasymov, S. Yevseiev, S. Milevskyi, N. Balitskyi, V. Zaika, S. Povaliaiev, S. Golovashych, O. Huk, A. Smirnov, K. Rubel, “Development of a method for automatic control of monitoring means for information protection objects,” East.-Eur. J. Enterp. Technol., vol. 6, no. 9(132), pp. 25–38, 2024. DOI: 10.15587/1729-4061.2024.319058.
[15] O. Bakaiev, I. Syvachenko, and V. Shevchenko, “Scalarization of the vector criterion of information system survivability based on information security indicators,” CEUR Workshop Proc., vol. 3826, pp. 294–300, 2024.
[16] A. M. Shutovskyi, “Some representations of triharmonic functions,” Cybern. Syst. Anal., vol. 60, no. 6, pp. 991–1000, 2024. DOI: 10.1007/s10559-024-00735-x.
[17] V. Khoroshko, Y. Khokhlachova, O. Laptiev, and A.-D. A. Fowad, “Mathematical apparatus for finding the optimal configuration secure communication network with a specified number of subscribers,” Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, vol. 15, no. 1, pp. 62–66, 2025. DOI: 10.35784/iapgos.6406.
[18] N. Kuchuk, O. Zakovorotnyi, S. Pyrozhenko, V. Radchenko, and S. Kashkevich, “A method for redistributing virtual machines of heterogeneous data centres,” Adv. Inf. Syst., vol. 9, no. 1, pp. 80–85, 2025. DOI: 10.20998/2522-9052.2025.1.09.
[19] L. Timchenko N. Kokriatska, V. Tverdomed, I. Yepifanova, Y. Didenko, D. Zhuk, M. Kozyr, I. Shakhina, “Architectural and structural and functional features of the organization of parallel-hierarchical memory,” Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, vol. 14, no. 1, pp. 46–52, 2024. DOI: 10.35784/iapgos.5615.

[20] L. Hotra, O. Boyko, I. Helzhynskyy, H. Barylo, M. Rozhdestvenska, H. Lastivka, "Functionally integrated device for temperature measurement," Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, vol. 14, no. 4, pp. 32–37, 2024. DOI: 10.35784/iapgos.6720.