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RESEARCH ARTICLE

Performance analysis and timing characteristics in industrial networks with random and deterministic node distributions

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Abstract

Objectives. The aim of the study was to develop mathematical tools to assess the performance and probabilistic-temporal characteristics of packet transmission processes in industrial networks employing random multiple access. Our study specifically examined strict packet delivery time constraints and the impact of collisions.

Methods. The research applies methods from the theory of random processes. We used the Laplace–Stieltjes transform to derive key relationships analytically and prove the main theorem.

Results. We formulated and proved a theorem which defines the Laplace–Stieltjes transform for the packet transmission time distribution function. The result incorporates packet retransmissions caused by conflicts in the multiple access environment. We analyzed information transmission processes in industrial networks with random multiple access, considering variations in the number of workstations and packet flow intensities at network nodes. Our evaluation included throughput, node and transmission medium utilization, and packet transmission times under collision conditions. The results reveal significant differences in the temporal characteristics of packet transmission between central and edge nodes. We developed and implemented a software package, in order to automate the study and evaluate various network operating modes during scaling and under increased nodal load.

Conclusions. The study of industrial networks with random multiple access established that while network throughput increases with the number of nodes during scaling, it degrades under significantly high node and transmission medium utilization. The utilization of edge nodes and their packet delivery times increase markedly faster than those of central nodes. This is due to a higher collision rate. As the network size increases, the performance and temporal characteristics exhibit only marginal dependence on the node distribution type: random or deterministic equidistant. In order to ensure balanced operation in an industrial network with random multiple access, we propose reducing the load on edge nodes by 10–15%. This strategy can maintain approximately uniform utilization of both the transmission medium and the nodes as their number increases.

Keywords: industrial network, performance, temporal characteristics, Laplace–Stieltjes transform, multiple access, scalability

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НАУЧНАЯ СТАТЬЯ

Анализ производительности и временных характеристик промышленных сетей со случайным и детерминированным эквидистантным распределением узлов

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Резюме

Цели. Цель работы – разработка математического аппарата для оценки производительности и вероятностно-временных характеристик процессов передачи пакетов в промышленных сетях, использующих метод случайного множественного доступа. Особенностью исследования является учет строгих ограничений на время доставки пакетов и влияние коллизий.

Методы. В основе исследования лежат методы теории случайных процессов. Для аналитического вывода ключевых соотношений и доказательства основной теоремы применяется аппарат преобразования Лапласа – Стильтеса.

Результаты. Сформулирована и доказана теорема, определяющая форму преобразования Лапласа – Стильтеса для функции распределения времени передачи пакета. Этот результат учитывает повторные передачи пакетов, вызванные конфликтами в среде с множественным доступом. Проведен анализ процессов передачи информации в промышленных сетях со случайным множественным доступом, включая изменение количества рабочих станций и интенсивности потоков пакетов. Анализировались пакеты, поступающие в узлы сети, оценивались производительность системы, степень загрузки узлов и канала передачи, а также время доставки пакетов с учетом возникающих конфликтов. Выявлено значительное различие во временных характеристиках передачи между центральными и периферийными узлами сети. Для автоматизации исследований и оценки различных режимов работы сети при ее масштабировании и увеличении нагрузки на узлы разработан и реализован программный комплекс.

Выводы. При проведении исследования промышленных сетей со случайным множественным доступом выявлено, что при масштабировании сети с увеличением количества узлов возрастает производительность сети, однако при значительном увеличении загрузки узлов и передающей среды производительность падает. Загрузка крайних узлов и время передачи пакетов из-за повышенного возрастания конфликтов возрастают значительно быстрее по сравнению с центральными узлами. Производительность и временные характеристики при увеличении количества узлов несущественно зависят от типа распределения узлов – случайного или детерминированного эквидистантного. Для обеспечения сбалансированности режимов работы промышленной сети со случайным множественным доступом предлагается на 10–15% уменьшить нагрузку на крайние узлы. При этом можно обеспечить примерно одинаковую загрузку передающей среды и узлов при увеличении их количества.

Ключевые слова: промышленная сеть, производительность, временные характеристики, преобразование Лапласа – Стильтеса, множественный доступ, масштабирование

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INTRODUCTION

When analyzing the effectiveness of industrial communication networks, the characteristics of data transmission processes occurring at the first three levels of the open systems interconnection (OSI) reference model need to be taken into account. These levels determine the correctness of frame formation, addressing, error control, and physical channel security.

One of the key requirements for industrial networks integrated into automated control systems for various purposes is the limitation on data delivery time. Compliance with this parameter is crucial for maintaining the required time indicators of technological processes and ensuring the stable operation of distributed control systems.

In order to evaluate the performance and probabilistic-temporal characteristics of data transmission processes, an industrial network was studied in which the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) method was implemented. This method provides shared access for multiple nodes to a common transmission medium by preemptively monitoring the channel status and stopping transmission when a signal conflict is detected. The data transmission channel bandwidth in the simulation was assumed to be equal to $C = 1$ Gbit/s, which corresponds to the characteristics of typical wired industrial Ethernet networks.

During the analysis, the dependencies of the study parameters on the number of network nodes were examined for both peripheral and central elements. The differences between random distribution of nodes along the communication line and their uniform (equidistant) placement were also considered.

1. LAPLACE-STIELTJES TRANSFORMATION THEOREM FOR PACKET TRANSMISSION TIME

As an integral indicator of industrial network efficiency, similar to the approach proposed in [1], the total intensity of data flow processed in a timely manner by all system nodes was used:

$$\lambda_{\text{tot}} = \sum_{i=1}^N \lambda_i Q_i, \quad (1)$$

wherein Q_i is the probability of timely delivery of packets arriving from the i th node; λ_i is the intensity of packets arriving at the i th node.

As shown in [1], the probability that no conflicts will arise when servicing a packet which has arrived at the k th node, no conflicts will arise, is estimated using the following formula:

$$q_k = \prod_{\substack{n=1 \\ n \neq k}}^N e^{-\lambda_n 2 \frac{L_{nk}}{V_{\text{med}}}}, \quad k = \overline{1, N}, \quad (2)$$

wherein N is the number of nodes in the network, L_{nk} is the distance between the k th and n th nodes in the network, and, V_{med} is the signal propagation speed in the transmission medium.

The probability P_n that a packet arriving at the k th node will be transmitted after exactly n attempts (i.e., $n - 1$ collisions will occur during transmission) is equal to:

$$P_n = (1 - q_k)^{n-1} q_k. \quad (3)$$

Based on the original results obtained earlier by A.S. Leontiev and published for the first time in 2001 on the development of mathematical methods for studying local networks [1], the following theorem can be formulated:

Theorem. The Laplace–Stieltjes transform $Z_k^*(s)$ of the distribution function of the packet transmission time from the k th node is estimated using the formula:

$$Z_k^*(s) = q_k T^*(s) \frac{1}{1 - (1 - q_k) X^*(s) V_k^*(s)}, \quad (4)$$

where $V_k^*(s) = \int_0^{\infty} e^{-st} dV_k(t)$ is the distribution function

of the packet resolution time coming from the k th node;

$X^*(s) = \int_0^{\infty} e^{-st} dX(t)$; $X(t)$ is the distribution function of

the delay time before packet retransmission in case of

a conflict; $T^*(s) = \int_0^{\infty} e^{-st} dT(t)$; $T(t)$ is the distribution

function of the packet transmission time without conflict.

Proof. Derivation of the Laplace–Stieltjes transform formula for the packet transmission time distribution function, taking into account possible conflicts.

The Laplace–Stieltjes transform for a function $F(t)$ which derivative is equal to $F'(t) = f(t)$ is defined as follows:

$$F^*(s) = \int_0^{\infty} e^{-st} f(t) dt.$$

The Laplace–Stieltjes transform is characterized by the multiplicative property [2–6]:

if random variables $\xi_{\Sigma} = \xi_1 + \xi_2 + \dots + \xi_N$ are independent and have distribution functions $F_i(t)$, then the Laplace–Stieltjes transform for the cumulative distribution function is defined as the product of the transforms of the individual functions:

$$F_{\Sigma}^*(s) = F_1^*(s) \cdot F_2^*(s) \cdot \dots \cdot F_N^*(s).$$

Let us apply this data to derive functional relationships for packet transmission times in industrial networks. Let P_n denote the probability that a packet will be successfully transmitted exactly on the n th attempt. In this case, the packet transmission time for n attempts can be expressed as follows:

$$\begin{aligned} \xi_{\text{trans}(n)} &= \xi_1 + \xi_2 + \dots + \xi_{n-1} + \eta_1 + \eta_2 + \dots + \\ &+ \eta_{n-1} + T_{\text{trans}} = \sum_{i=1}^{n-1} \xi_i + \sum_{i=1}^{n-1} \eta_i + T_{\text{trans}}, \end{aligned}$$

wherein ξ_i is the resolution time of the i th conflict;

$\sum_{i=1}^{n-1} \xi_i$ is the total resolution time of $n - 1$ conflicts;

η_i is the delay time before retransmitting the packet

when the i th conflict occurs; $\sum_{i=1}^{n-1} \eta_i$ is the total delay

time when $n - 1$ conflicts occur; T_{trans} is the packet transmission time (n th attempt).

If all ξ have the same distribution function $V(t)$, and all η have the same distribution function $X(t)$, then the Laplace–Stieltjes transform of the distribution function of the packet transmission time exactly after n attempts will take the form:

$$B_n^*(s) = (V_k^*(s))^{n-1} (X^*(s))^{n-1} T^*(s).$$

The Laplace–Stieltjes transform of the packet transmission time distribution function from the k th node, taking into account the conflicts that arise, will be determined by the expression:

$$Z_k^*(s) = \sum_{n=1}^{\infty} P_n B_n^*(s) = \tag{5}$$

$$= \sum_{n=1}^{\infty} [P_n (X^*(s))^{n-1} (V_k^*(s))^{n-1} T^*(s)],$$

$$Z_k^*(s) =$$

$$= \sum_{n=1}^{\infty} (1 - q_k)^{n-1} q_k (X^*(s))^{n-1} (V_k^*(s))^{n-1} T^*(s) = \tag{6}$$

$$= q_k T^*(s) \frac{1}{1 - (1 - q_k) X^*(s) V_k^*(s)},$$

wherein $q_k T^*(s)$ is the first term, and $(1 - q_k) X^*(s) V_k^*(s)$ is the denominator of an infinitely decreasing geometric progression. Expression (6) coincides with formula (4), which proves the theorem.

Differentiating the resulting expression with respect to s , we obtain expressions for $Z_k^{(1)}$ and $Z_k^{(2)}$ of the distribution function, $Z_k(t)$, $B_k^{(1)}$, $B_k^{(2)}$. They can be used to derive functional relationships for the packet transmission times in networks [1, 2, 7].

During modeling, the network length was assumed to be 500 and 1000 m, respectively. The distribution of nodes in the network can be deterministic with equal intervals or random. In the case of random distribution, the positions of the nodes were set arbitrarily [8–16].

2. RESULTS OF THE ANALYSIS OF INDUSTRIAL NETWORK CHARACTERISTICS

The communication channel bandwidth was assumed to be $C = 1$ Gbit/s during modeling, and the speed of electromagnetic signal propagation along the line was $V_c = 2.9 \cdot 10^8$ m/s. The maximum retransmission delay upon collision detection (overlap of packets transmitted simultaneously) was $\tau = 0.0005$ s. A packet with a length of $L_{\text{int}} = 36$ bits was used, in order to simulate interference. The directive transmission time of one packet was taken to be equal to $T_{\text{dir}}^{(1)} = 0.001$ s, and the length of the transmitted packet is $L_{\text{pack}} = 4096$ bits. The intensity of data arrival at the nodes of the simulated network (λ_n) varied from 1200 to 1800 pack/s with an interframe interval of $\Delta t = 0.0005$ s.

The results of the numerical experiment are shown in Figs. 1–7. Analysis of the dependencies (Fig. 1) shows that with an increase in the number of network nodes and their random placement along the length of the communication line $L_{\text{network}} = 500$ m, as well as with a traffic intensity of $\lambda_n = 1800$ pack/s, $N = 1,110$, a uniform load ρ is achieved in the central sections of the network and the transmission channel. At the same time, the border nodes demonstrate a higher load level,

exceeding the average value by approximately 10–15%. This is due to an increase in the probability of packet conflicts at the network boundaries where mutual interference is more frequently observed. The results confirm the influence of the geometric location of nodes and the topological features of the network on the efficiency of the data transmission channel. This leads to a significant increase in the transmission time of packets from edge nodes when scaling the network due to the high load on edge nodes. The load remains virtually the same even with a deterministic equidistant distribution of nodes along the network length.

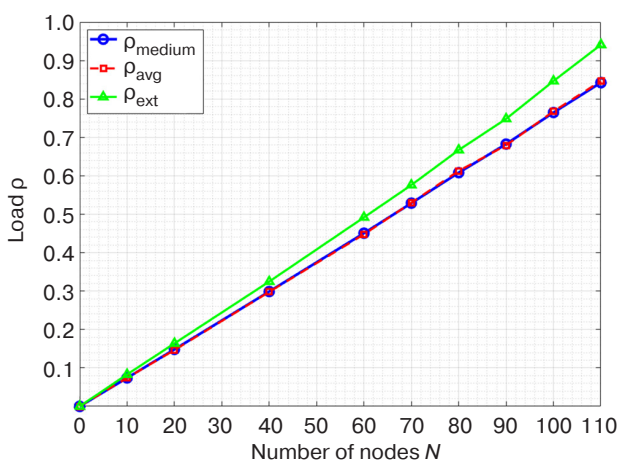


Fig. 1. Loads of the transmission medium (ρ_{medium}), extreme (ρ_{ext}), and average (ρ_{avg}) nodes with random distribution of nodes in the network

Figure 2 shows the dependence of packet transmission time on the number of network nodes N at a packet arrival rate $\lambda_n = 1800$ pack/s, where the delivery time from the average and extreme nodes is compared for two node distribution schemes: random and deterministic equidistant. The influence of network topology and node location on delivery characteristics is also shown.

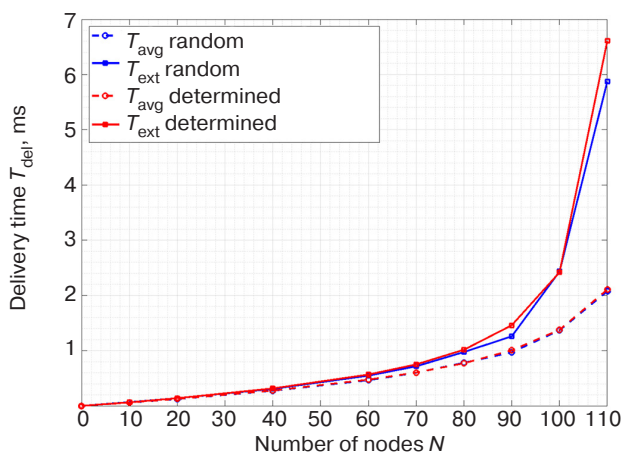


Fig. 2. Delivery time for packets arriving from the average (T_{avg}) and extreme (T_{ext}) nodes with random and deterministic equidistant distribution

The average delivery time for packets coming from extreme nodes given a large number of nodes (and accordingly when heavily loaded), can exceed the average delivery time for packets coming from middle nodes by several times. This was observed both in the case of random and deterministic equidistant node distribution. The time characteristics of packet transmission with random and deterministic equidistant placement differ insignificantly when scaling the network.

Figure 3 shows how the probability of timely delivery of Q packets depends on the total number of nodes N in the network. The analysis was performed separately for packets arriving from average and extreme nodes with a traffic generation intensity of $\lambda_n = 1800$ pack/s at each node. The graph allows us to compare how different node distribution schemes—random and deterministic equidistant—affect the guarantee of timely delivery for different categories of nodes when scaling the network. When scaling the network (increasing the number of nodes), the probability of timely packet delivery drops sharply. This drop is more pronounced for the edge nodes of the network. The nature of the network node distribution (random or deterministic equidistant) has less of an impact on the probability of timely packet delivery.

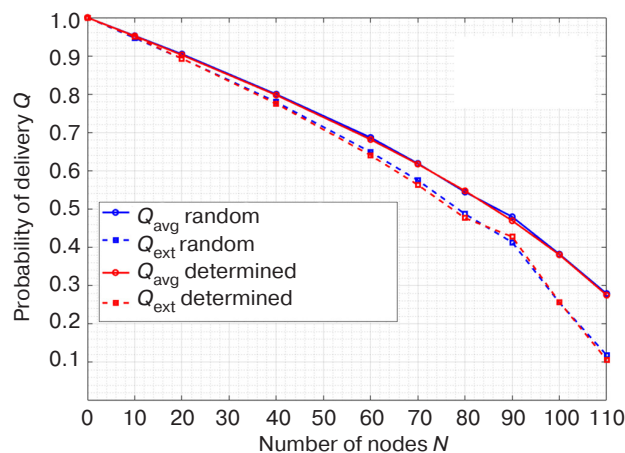


Fig. 3. Probability of timely delivery of packets coming from the middle (Q_{avg}) and extreme (Q_{ext}) nodes with random and deterministic equidistant distribution of nodes

Figure 4 shows the dependence of network performance λ_{tot} on the total number of nodes N . The study was conducted for a constant packet generation rate by each node, equal to $\lambda_n = 1800$ pack/s, $N = 1,110$. The graph allows us to compare the effect of network topology (random and deterministic equidistant distribution of nodes) on throughput. Analysis of the curves shows how network scaling affects its overall performance under different organizational principles.

As can be seen in Fig. 4, the type of node distribution (random or deterministic) has no significant

effect on performance. When scaling the network by increasing the number of nodes, performance first increases, then reaches a maximum and drops sharply. This is due to the fact that as the number of nodes increases, the load on the nodes and the transmission medium increases, the packet transmission time increases sharply, and, accordingly, the probability of processing packets within a time not exceeding the directive decreases. This leads to a decrease in performance.

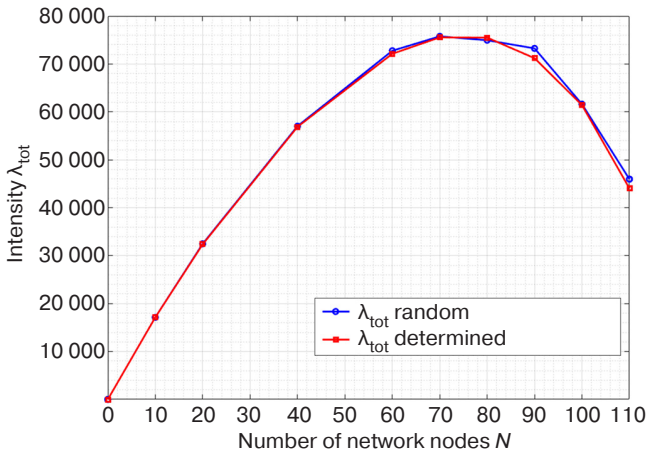


Fig. 4. Network performance with random and deterministic equidistant distribution of network nodes

Figures 5–7 demonstrate how the main characteristics of an industrial network with random multiple access change when scaled down when the intensity of packets arriving at network nodes decreases to $\lambda_n = 1200$ pack/s, $N = 1,110$.

Figure 5 shows how the number of nodes N in a network affects the load on its key elements: the transmission medium, as well as the edge and middle nodes. The data was obtained for two topology scenarios: with deterministic and random node placement at an incoming traffic intensity of $\lambda_n = 1200$ pack/s at each node. The graphs show that the load on the nodes and the transmission medium does not significantly depend on the type of node distribution, but depends significantly on the length of the network. As can be seen from the graphs, the load on the transmission medium increases much faster than the load on the nodes. At the same time, with a reduced intensity of the incoming packet flow, the growth in the load on both the nodes and the transmission medium occurs much more slowly as the network scales up. This indicates more stable system operation under moderate loads. The maximum values of the transmission channel and network node load, taking into account the influence of collisions, are achieved only with a larger total number of active network elements. This confirms the dependence of the system’s efficiency on the density of its topological structure and traffic intensity. In

this case in particular, the critical number of nodes N is equal to 190, while at $\lambda_n = 1800$ pack/s the critical value is $N = 110$ (Fig. 1).

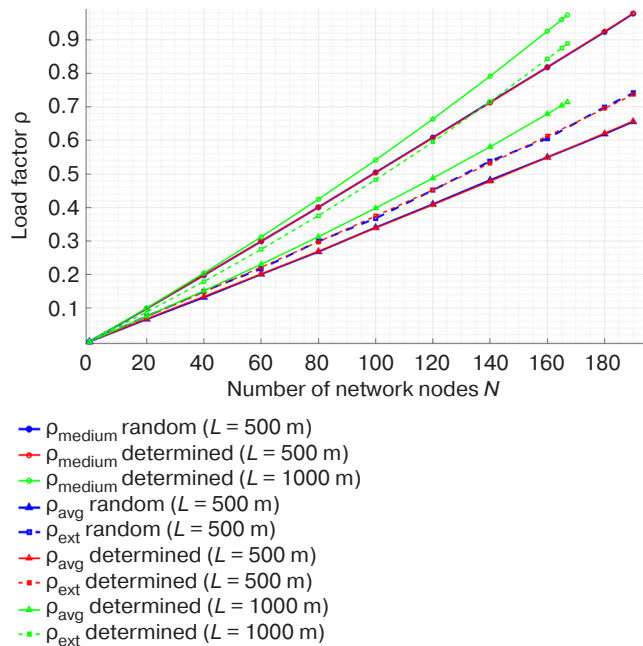


Fig. 5. Dependence of the transmission medium load (ρ_{medium}), extreme (ρ_{ext}), and average (ρ_{avg}) network nodes under deterministic and random distribution with different network lengths

Figure 6 shows the effect of the total number of network nodes N on the packet delivery time T_{del} . The dependence was analyzed separately for packets generated by nodes located at the network boundary and nodes located at its center. In all experiments, the load intensity generated by each node was fixed and equal to $\lambda_i = 1200$ pack/s. The graph allows us to estimate how the choice of network topology—deterministic or random node distribution—affects data transmission delays when the system scale changes.

As can be seen from the graphs, the type of node distribution (random or deterministic) does not significantly affect the temporal characteristics when scaling the network. In the critical operating area ($N = 190$) the packet transmission time is significantly less than in the critical operating area at a packet arrival rate of $\lambda_n = 1800$ pack/s, $n = 1, N$. It was established that the critical value of the number of network nodes is $N = 110$. When this threshold is reached, the system transitions to saturation mode, as characterized by a change in the ratio between the load on the nodes and the data transmission channel. Analysis of the dependencies obtained (Figs. 2 and 6) showed that when the transmission medium is overloaded, the difference in the time characteristics of packet transmission between peripheral and central nodes is significantly less than in the case of overload of the

extreme nodes of the network. This indicates that under high loads, the data transmission channel becomes the determining factor in equalizing delays across the entire length of the network. Hence, it follows that when scaling an industrial network, the principle of balance should be observed, i.e., the load on the transmission medium and the load on the nodes should change approximately equally, taking into account the conflicts which may arise. To achieve this, not only must the intensity of the flows entering the nodes be selected in such a way that the load on the central nodes corresponds to the load on the transmission medium, but also the intensity of the packet flows coming for processing from the extreme nodes be reduced by 10–15% compared to the central nodes.

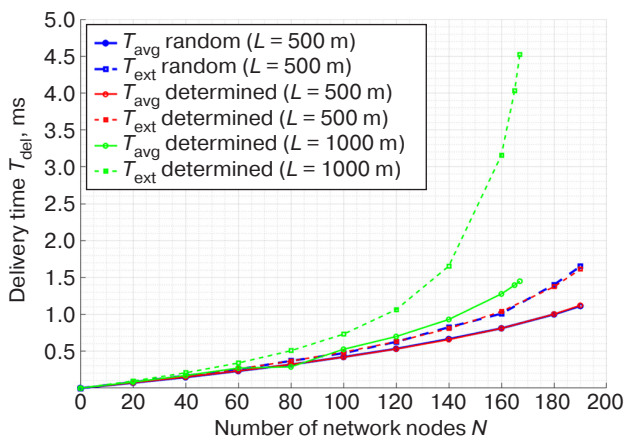


Fig. 6. Delivery time of packets arriving from the average (T_{avg}) and extreme (T_{ext}) nodes with random and deterministic node distribution for different network lengths

According to the data in Fig. 7, the performance λ_{tot} of an industrial network demonstrates the expected dependence on scale: it decreases with an increase in the number of the nodes N . However, the key result is that the type of topology (both random and deterministic equidistant distribution of nodes) does not have a significant effect on performance. This conclusion is confirmed by the graphs constructed for incoming traffic intensity $\lambda_i = 1200$ pack/s. They also indicate the dominant role of the total number of nodes, rather than their spatial distribution, in determining network throughput.

The drop in performance in the critical area of operation caused by heavy transmission medium load at $N = 160$ – 190 (Fig. 7) is significantly weaker than in the critical area caused by heavy load on the extreme nodes at $N = 90$ – 110 (Fig. 4). This is caused by the fact that the time characteristics of packet transmission increase more sharply with a high load on the extreme nodes, taking into account potential conflicts, (Fig. 2) when compared to a high load on the transmission medium (Fig. 6).

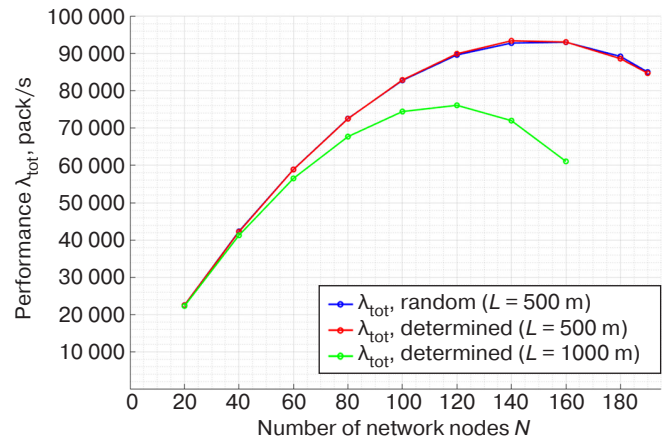


Fig. 7. Network performance λ_{tot} with a random and deterministic equidistant distribution of network nodes at different network lengths and packet arrival rates at network nodes $\lambda_i = 1200$ pack/s, $i = \overline{1, N}$

CONCLUSIONS

The performance and probabilistic-temporal characteristics of industrial networks with random multiple access were evaluated, taking into account restrictions on packet transmission time. The study formulated and then proved a theorem on the Laplace–Stieltjes transform of the packet transmission time distribution function, taking into account emerging conflicts.

The study also conducted an analysis of information transfer processes in industrial networks with random multiple access. It included changes in the number of workstations and the intensity of packet flows arriving at network nodes. A set of programs was developed and implemented, in order to automate research and evaluate various network operating modes during scaling and increased load on nodes.

The simulation showed that in the initial stages of network scaling, accompanied by an increase in the number of active nodes, there is an increase in its overall performance due to the more efficient use of available channel bandwidth. However, with a further increase in traffic intensity and load on both nodes and the transmission medium, the system’s performance begins to decline. At the same time, there is a sharp increase in packet transmission delays, indicating a decrease in the efficiency of data exchange at high network traffic density. In addition, the study established that nodes located at the periphery of the network are characterized by a faster increase in packet transmission time and load level when compared to the central elements of the topology. This is due to the increased likelihood of collisions and signal interference arising from simultaneous attempts to transmit data at the edge of the network.

Taking into account potential conflicts when the number of nodes increases, studies have shown that performance and timing characteristics do not significantly depend on the type of node distribution: random or deterministic equidistant. However, they do depend significantly on the length of the network. The study also showed that the timing characteristics of packet transmission, taking into account emerging conflicts, increase more sharply with high load on the extreme nodes when compared to high load on the transmission medium.

It can be thus concluded that when scaling an industrial network, the principle of balance should be

observed. The load on the transmission medium and the load on the nodes should change approximately equally, taking into account emerging conflicts. In order to achieve this, not only must the intensity of the flows entering the nodes be selected in such a way that the load on the central nodes corresponds to the load on the transmission medium, but also the intensity of the packet flows coming for processing from the extreme nodes be reduced by 10–15% when compared to the central nodes.

Authors' contribution. All authors contributed equally to the research work.

REFERENCES

1. Zhmatov D.V., Leontyev A.S. Analysis of information transmission processes in multimode fiber-optic networks with a token-based access method. *Russian Technological Journal*. 2025;13(5):41–50. <https://doi.org/10.32362/2500-316X-2025-13-5-41-50>
2. Leontyev A.S. Development of Analytical Methods, Models, and Techniques for Local Area Networks Analysis. In: *Theoretical Issues of Software Engineering: Interuniversity Collection of Scientific Papers*. Moscow: MIREA; 2001. P. 70–94 (in Russ.).
3. Leontyev A.S., Zhmatov D.V. Study of the probabilistic and temporal characteristics of wireless networks using the CSMA/CA access method. *Russian Technological Journal*. 2024;12(2):67–76. <https://doi.org/10.32362/2500-316X-2024-12-2-67-76>
4. Ferguson C., Kleinrock L. Optimal Update Times for Stale Information Metrics Including the Age of Information. *IEEE Journal on Selected Areas in Information Theory*. 2023;4:734–746. <https://doi.org/10.1109/JSAIT.2023.3344760>
5. He Z., Kleinrock L. Optimization of Assisted Search Over Server-Mediated Peer-to-peer Networks. In: *GLOBECOM 2022 – 2022 IEEE Global Communications Conference*. Rio de Janeiro, Brazil. 2022. P. 4928–4934. <https://doi.org/10.1109/GLOBECOM48099.2022.10000846>
6. Sapna, Sharma M. Performance evaluation of a wired network with & without Load Balancer and Firewall. In: *2010 International Conference on Electronics and Information Engineering*. Kyoto, Japan. 2010. P. V2-515–V2-519. <https://doi.org/10.1109/ICEIE.2010.5559755>
7. Smirnova E.V. *Tekhnologii sovremennykh setei Ethernet. Metody kommutatsii i upravleniya potokami dannykh (Technologies of Modern Ethernet Networks. Methods of Switching and Data Flow Control)*. Moscow: BHV-Peterburg; 2017, 480 p. (in Russ.).
8. Ivanichkina L.V., Neporada A.L. The reliability model of a distributed data storage in case of explicit and latent disk faults. *Trudy Instituta sistemnogo programmirovaniya RAN = Proceedings of the Institute for System Programming of the RAS*. 2015;27(6):253–274 (in Russ.). [https://doi.org/10.15514/ISPRAS-2015-27\(6\)-16](https://doi.org/10.15514/ISPRAS-2015-27(6)-16)
9. Wei M., Chen Z. Study of LANs access technologies in wind power system. In: *IEEE PES General Meeting*. Minneapolis, MN, USA. 2010. <https://doi.org/10.1109/PES.2010.5590088>
10. AlshaeV I.A., Lavrukhin V.A. Wi-Fi networks design and optimization. *Informatsionnye tekhnologii i telekommunikatsii = Telecom IT*. 2016;4(1):87–95 (in Russ.). <https://www.elibrary.ru/wbdxbt>
11. Zvonareva G.A., Buzunov D.S. Using Simulation Modeling to Estimate Time Characteristics of a Distributed Computing System. *Otkrytoe obrazovanie = Open Education*. 2022;26(5):32–39 (in Russ.). <https://doi.org/10.21686/1818-4243-2022-5-32-39>
12. Talalaev A.A., Frolenko V.P. Fault-tolerant system for organizing high-performance computing for solving data stream processing problems. *Programmnye sistemy: Teoriya i prilozheniya = Program Systems: Theory and Applications*. 2018;9(1-36): 85–108 (in Russ.). <https://doi.org/10.25209/2079-3316-2018-9-1-85-108>
13. Pavsky V.A., Pavsky K.V. Mathematical Model for Calculating Reliability Indicators of Scalable Computer Systems Considering Switching Time. *Izvestiya YuFU. Tekhnicheskie nauki = Izvestiya SFedU. Engineering Sciences*. 2020;2(212):134–145 (in Russ.). <https://doi.org/10.18522/2311-3103-2020-2-134-145>
14. Ahmed W., Wu Y.W. A survey on reliability in distributed systems. *J. Comput. System Sci*. 2013;79(8):1243–1255. <https://doi.org/10.1016/j.jcss.2013.02.006>
15. Bakhareva N.F. Performance analysis of network structures by methods of queuing theory. *Informatika, telekommunikatsii i upravlenie = Computing, Telecommunication and Control*. 2009;3(80):25–34 (in Russ.). <https://www.elibrary.ru/kxxbqv>
16. Sharafullina A.Yu., Galyamov R.R., Zaripova R.S. Technical principles for creating a wireless local network Wi-Fi. *T-Comm: Telekommunikatsiya i transport = T-Comm*. 2021;15(7):28–33 (in Russ.). <https://doi.org/10.36724/2072-8735-2021-15-7-28-33>

СПИСОК ЛИТЕРАТУРЫ

1. Жматов Д.В., Леонтьев А.С. Анализ процессов передачи информации в многомодовых оптоволоконных сетях с маркерным методом доступа. *Russian Technological Journal*. 2025;13(5):41–50. <https://doi.org/10.32362/2500-316X-2025-13-5-41-50>
2. Леонтьев А.С. Разработка аналитических методов, моделей и методик анализа локальных вычислительных сетей. *Теоретические вопросы программного обеспечения: Межвузовский сборник научных трудов*. М.: МИРЭА; 2001. С. 70–94.
3. Леонтьев А.С., Жматов Д.В. Исследование вероятностно-временных характеристик беспроводных сетей с методом доступа CSMA/CA. *Russian Technological Journal*. 2024;12(2):67–76. <https://doi.org/10.32362/2500-316X-2024-12-2-67-76>
4. Ferguson C., Kleinrock L. Optimal Update Times for Stale Information Metrics Including the Age of Information. *IEEE Journal on Selected Areas in Information Theory*. 2023;4:734–746. <https://doi.org/10.1109/JSAIT.2023.3344760>
5. He Z., Kleinrock L. Optimization of Assisted Search Over Server-Mediated Peer-to-peer Networks. In: *GLOBECOM 2022 – 2022 IEEE Global Communications Conference*. Rio de Janeiro, Brazil. 2022. P. 4928–4934. <https://doi.org/10.1109/GLOBECOM48099.2022.10000846>
6. Sapna, Sharma M. Performance evaluation of a wired network with & without Load Balancer and Firewall. In: *2010 International Conference on Electronics and Information Engineering*. Kyoto, Japan. 2010. P. V2-515–V2-519. <https://doi.org/10.1109/ICEIE.2010.5559755>
7. Смирнова Е.В. *Технологии современных сетей Ethernet. Методы коммутации и управления потоками данных*. М.: БХВ-Петербург; 2017, 480 с.
8. Иваничкина Л.В., Непорада А.Л. Модель надежности распределенной системы хранения данных в условиях явных и скрытых дисковых сбоев. *Труды Института системного программирования РАН*. 2015;27(6):253–274. [https://doi.org/10.15514/ISPRAS-2015-27\(6\)-16](https://doi.org/10.15514/ISPRAS-2015-27(6)-16)
9. Wei M., Chen Z. Study of LANs access technologies in wind power system. In: *IEEE PES General Meeting*. Minneapolis, MN, USA. 2010. <https://doi.org/10.1109/PES.2010.5590088>
10. Альшаев И.А., Лаврухин В.А. О проектировании и оптимизации сетей Wi-Fi. *Информационные технологии и телекоммуникации*. 2016;4(1):87–95. <https://www.elibrary.ru/wbdxht>
11. Звонарева Г.А., Бузунов Д.С. Использование имитационного моделирования для оценки временных характеристик распределенной вычислительной системы. *Открытое образование*. 2022;26(5):32–39. <https://doi.org/10.21686/1818-4243-2022-5-32-39>
12. Талалаев А.А., Фроленко В.П. Отказоустойчивая система организации высокопроизводительных вычислений для решения задач обработки потоков данных. *Программные системы: Теория и приложения*. 2018;9(1-36):85–108. <https://doi.org/10.25209/2079-3316-2018-9-1-85-108>
13. Павский В.А., Павский К.В. Математическая модель для расчета показателей надежности масштабируемых вычислительных систем с учетом времени переключения. *Известия ЮФУ. Технические науки*. 2020;2(212):134–145. <https://doi.org/10.18522/2311-3103-2020-2-134-145>
14. Ahmed W., Wu Y.W. A survey on reliability in distributed systems. *J. Comput. System Sci*. 2013;79(8):1243–1255. <https://doi.org/10.1016/j.jcss.2013.02.006>
15. Бахарева Н.Ф. Анализ производительности сетевых структур методами теории массового обслуживания. *Информатика, телекоммуникации и управление*. 2009;3(80):25–34. <https://www.elibrary.ru/kxxbqv>
16. Шарафуллина А.Ю., Галямов Р.Р., Зарипова Р.С. Технические принципы создания беспроводной локальной сети Wi-Fi. *Т-Сотт: Телекоммуникация и транспорт*. 2021;15(7):28–33. <https://doi.org/10.36724/2072-8735-2021-15-7-28-33>

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