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RESEARCH ARTICLE

Study of the probabilistic and temporal characteristics of wireless networks using the CSMA/CA access method

Alexander S. Leontyev,
Dmitry V. Zhmatov [@]

MIREA – Russian Technological University, Moscow, 119454 Russia
[@] Corresponding author, e-mail: zhmatov@mirea.ru

Abstract
Objectives. The aim of this study is to develop analytical methods to evaluate the probabilistic and temporal characteristics and performance of wireless networks using the CSMA/CA access method. These methods enable the process of selecting rational operating modes to be automated and the impact of collisions in networks implementing the 802.11 protocols to be reduced.
Methods. The methods employed herein include reliability theory, theory of random processes, queuing theory, and the Laplace–Stieltjes transform.
Results. A problem statement is presented and developed, along with an analytical method for evaluating the probabilistic and temporal characteristics and performance of wireless networks using the CSMA/CA access method. This method considers time constraints on information transmission, thus expanding the applicability of previously proposed analytical approaches for studying Ethernet local area networks. The analysis of networks that use the CSMA/CA access method was carried out. An original mathematical model was developed that allows evaluating various characteristics of packet transmission processes in wireless networks under time constraints on the transmission. These characteristics include latency, packet transfer time, node load, and network performance. A software package was developed to simplify the analysis and evaluation of various operation modes of wireless networks using the CSMA/CA access method.
Conclusions. We demonstrate the need for developing nested analytical models describing packet transmission processes in wireless networks under time constraints on link-layer transmission. This implies the development of more complex models for more exact description of packet transmission processes in such networks. The software package developed herein enables the various options for the functioning of the network to be studied and analytical calculations to be performed. Calculations were carried out, in order to assess the probabilistic and temporal characteristics of packet transmission processes and the wireless network performance. The research involved varying the number of workstations and the intensity of packet flows entering the network nodes under the time constraint on packet transmission. The application of the developed mathematical models will be useful in creating and optimizing wireless networks such as Wi-Fi networks, networks based on the IEEE 802.11 standard, and other data transmission systems using the CSMA/CA access method. Such models and the analysis based on them will be useful in optimizing network performance, adjusting parameters, as well as selecting the capacity and configuration of wireless networks.

Keywords: analytical method, mathematical model, wireless networks, jam packets, CSMA/CA, 802.11 standard, temporal characteristics

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НАУЧНАЯ СТАТЬЯ

Исследование вероятностно-временных характеристик беспроводных сетей с методом доступа CSMA/CA

А.С. Леонтьев,
Д.В. Жматов @

МИРЭА – Российский технологический университет, Москва, 119454 Россия
@ Автор для переписки, e-mail: zhmatov@mirea.ru

Резюме
Цели. Целью статьи является разработка аналитических методов оценки вероятностно-временных характеристик и производительности беспроводных сетей с методом доступа CSMA/CA, позволяющих автоматизировать процессы выбора рациональных режимов работы и снизить влияние наложений в сетях, реализующих протоколы 802.11.
Методы. Использованы методы теории надежности, теории случайных процессов и теории массового обслуживания, преобразование Лапласа – Стилтьеса.
Результаты. Разработан аналитический метод оценки вероятностно-временных характеристик и производительности беспроводных сетей с методом доступа CSMA/CA с учетом ограничений на время передачи информации. Метод расширяет область применимости аналитических подходов, предложенных ранее для исследования локальных сетей Ethernet. Проведен анализ сетей, которые используют метод доступа CSMA/CA. Разработана оригинальная математическая модель, позволяющая оценить различные характеристики процессов передачи пакетов в беспроводных сетях при ограничениях на время передачи. Эти характеристики включают время ожидания, время передачи пакетов, загрузку узлов и производительность сети. Для упрощения анализа и оценки различных режимов работы беспроводных сетей с методом доступа CSMA/CA был разработан программный комплекс.
Выводы. Показана необходимость первоочередной разработки вложенных аналитических моделей, описывающих процессы передачи пакетов в беспроводных сетях при ограничениях на время передачи информации на канальном уровне. Это означает, что для более точного описания процессов передачи пакетов в таких сетях требуется создание более сложных моделей. Разработанный программный комплекс позволяет изучать различные варианты функционирования сети и проводить аналитические расчеты. Были проведены расчеты для оценки вероятностно-временных характеристик процессов передачи пакетов и производительности беспроводной сети. Исследования включали изменение количества рабочих станций и интенсивности потоков пакетов, поступающих в узлы сети, при ограничении времени передачи пакетов. Применение разработанных математических моделей может быть полезным при создании и оптимизации беспроводных сетей, таких как Wi-Fi-сети, сети связи на основе стандарта IEEE 802.11 и другие системы передачи данных с использованием метода доступа CSMA/CA. Такие модели и анализ на их основе различных режимов функционирования беспроводных сетей могут помочь в оптимизации производительности сетей, настройке параметров, а также при выборе емкости и конфигурации беспроводных сетей.

Ключевые слова: аналитический метод, математическая модель, беспроводные сети, jam-пакеты, CSMA/CA, стандарт 802.11, временные характеристики

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INTRODUCTION

The search for new ways of improving the performance of wireless local area network (WLAN) is driven by the dramatic increase in the number of Wi-Fi enabled devices, as well as by the intense growing demand.

In order to achieve a high quality of streaming, WLAN uses a common physical medium to exchange data between active devices. An important challenge in WLAN is to control access to the physical medium. In the most common Wi-Fi networks, the medium access station uses carrier sensing multiple access with collision avoidance (CSMA/CA). The use of a portion of the network bandwidth for CSMA/CA implementation reduces network bandwidth for subscriber traffic, thus negatively impacting wireless network performance.

The methods used to access the physical medium of wireless networks play an important role in the operation of the medium access control (MAC) sublayer. Access to the WLAN physical medium is governed by the IEEE 802.11 standard[1]. The most widely used MAC address is based on the CSMA/CA scheme. The scheme provides competitive access to the physical medium.

In early IEEE 802.11 versions, the CSMA/CA mechanism is implemented as a distributed coordination function which provides equal access to all nodes in the network.

In addition, in AP-centric networks, the IEEE 802.11 standard implements a point coordination function which provides centralized access to the physical medium. The distributed coordination function does not maintain the quality of service (QoS).

In general terms, higher priority frames have more chance of being transmitted, while the channel load is reduced. There have been many studies aimed at improving the performance of the MAC sublayer using different techniques and approaches. While most of them focus on ensuring the transmission of different types of traffic, the impact of different ratios of traffic types on network performance has not yet been studied. Knowing this would enable the development of specialized algorithms for improving the information transmission in wireless networks.

The MAC sublayer is oriented towards specific ratios of traffic types in each particular application.

The development of mathematical methods to estimate node load, transmission medium, time characteristics, and performance of local and wireless networks allows the design process [1, 2] to be automated, thus resulting in improved network efficiency. Modern network technologies and protocols are described in [3, 4].

The main research techniques of multimachine computing systems and local networks include methods based on the reliability theory [5–7], queuing theory, and simulation modeling [8–15]. Known analytical research techniques do not consider directive constraints on the packet transmission time in wireless networks. For the CSMA/CA access method, certain ratios of the “transmission rate/frame size” and “network size/frame size” parameters need to be maintained.

This paper presents an original analytical model for evaluating the probabilistic and temporal characteristics and performance of wireless networks with CSMA/CA access method under directive constraints on the information transmission time. It thus develops the well-known analytical research techniques for Ethernet networks [16].

1. CHARACTERIZING THE CSMA/CA ACCESS METHOD

The probability of data transmission error is much higher in a wireless medium rather than in a wired medium. The transmitted signal strength is much higher than that of the received signal. The operating range of transmitters is limited in this case, so not all the computers on the Wi-Fi network are able to receive the transmitted data. This results in a number of problems. The most prominent of these are hidden and

[1] IEEE 802.11 is a set of communication standards for communication in the wireless local area networking frequency bands of 2.4, 3.6, and 5 GHz.

exposed terminal problems [11, 12]. In the Ethernet network, the carrier senses multiple access using the collision detection or CSMA/CD access method, since conflicts are relatively cheap. They are detected almost immediately, and computers stop the transmission at once [4]. In Wi-Fi wireless networks, the carrier senses multiple access using the conflict avoidance or CSMA/CA access method, since collisions are very expensive [9, 10]. In [11, 12], modern data transmission technologies and prospects for their development are considered.

The CSMA/CA access method is most often used in wireless networks in which operation at the physical layer is described by the ISO/OSI (International Organization for Standardization / Open Systems Interconnection) model and 802.11 standard. In particular, the IEEE 802.11x, 802.11ac, 802.11ax, and 802.11be communication standards are used in high-speed Wi-Fi networks [16]. The CSMA/CA method demonstrates a high level of efficiency in compact wireless networks with a small number of nodes.

With an increasing number of workstations and workload, a dramatic decrease in the efficiency of the wireless network can be observed. These two factors inevitably increase the number of conflicts and result in more time spent on resolving them. Unlike methods for studying cable or fiber-optic local area networks [16], analytical methods used in studying probabilistic and temporal characteristics of wireless networks are not sufficiently developed. When developing models based on simulation techniques [13, 14] it can be cumbersome and time-consuming to achieve reliable results in the entire research area of CSMA/CA-enabled transport medium and network node load. This is because the number of conflicts is highly dependent on the load. In addition, this model is nested with respect to models used to estimate the probabilistic and temporal characteristics of information processes in the distributed computing system. Thus, calculations require its multiple use, dramatically increasing the time required for study.

Networks which implement 802.11 protocols require analytical methods for evaluating probabilistic and temporal characteristics to be developed. They also require the implementation of wireless networks with CSMA/CA access method, thus allowing the processes of selecting rational operating modes to be automated and the impact of collisions to be reduced. These factors represent both relevant and indisputable novelty.

2. PROBLEM STATEMENT

Given:

1. The transmitting medium of wireless network is ether.
2. Access to the transmitting medium is CSMA/CA.
3. The number of nodes in the wireless network is N.
4. Placement of nodes. The main characteristic: the distance between the nodes in the network is L_{ik}, m, (i and k are node numbers).
5. Bandwidth is c, Mbit/s.
6. Signal propagation speed is V_c, m/s.
7. Delay in the jampack retransmission when conflicts are detected is τ, s.
8. Jampack size is L_{jam}, bit.
9. Delay in receiving confirmation for the transmitted jampack is Δt_{jam}, s.
10. Info pack length is L_{pack}, bits.
11. Directive time of the info pack transmission is $T_{dir}^{(1)}$, s.
12. Streams of packs coming to the wireless network nodes is λ_k, pack/s $(k=\overline{1,N})$.
13. Interframe interval is Δt, s.

To be defined:

1. $T_k^{(1)}$ is the delivery time of info packs $(k=\overline{1,N})$.
2. Q_k is probability of the info pack on-time delivery $(k=\overline{1,N})$.
3. λ_{sum} is network performance.
4. Load of nodes and transmission medium of wireless network.

The wireless network performance is defined as the total intensity of the on-time served stream.

3. MATHEMATICAL MODEL OF THE METHOD FOR EVALUATING WIRELESS NETWORK CHARACTERISTICS

The problem is resolved under the assumption of the Poisson nature of streams λ_k $(k=\overline{1,N})$, coming to the wireless network nodes for service.

When transmitting a jampack from the kth node, a conflict occurs if node i starts transmitting a jampack in the interval $(0, T_{ik}]$, or node i starts transmitting a jampack in the interval $[-T_{ik}, 0)$, as follows:

$$\{T_{ik}=L_{ik}/V_c,\ i=\overline{1,N},\ i\neq k\}.$$

The probability that node i will not start transmission in the interval $2T_{ik}$ with a Poisson stream of packets arriving at the nodes of the network is determined by ratio $e^{-\lambda_i 2T_{ik}}$.

Then the probability that the transmission of a jampack from the kth node will not cause conflicts with jampacks transmitted from other nodes in the network can be evaluated using the following formula:

$$g_k=\prod_{i=1,i\neq k}^{N} e^{-\lambda_i 2T_{ik}},\ k=\overline{1,N}. \quad (1)$$

Let $P_k^*(s) = \int_0^\infty e^{-st} dP_k(t)$ be the Laplace–Stieltjes transform of the distribution function $P_k(t)$ of the packet transmission time from the *k*th node allowing for emerging conflicts, and let *s* be a complex parameter. $P_k^*(s)$ is defined by the following expression:

$$P_k^*(s) = \sum_{n=1}^{\infty} \left\{ P_n (X^*(s))^{n-1} \cdot (V_k^*(s))^{n-1} F^*(s) \right\}, \quad (2)$$

where $P_n = (1 - g_k)^{n-1} g_k$ is the probability that the packet will be transmitted in exactly *n* attempts (when transmitting jampack, conflicts will occur $n - 1$ times); $F^*(s) = \int_0^\infty e^{-st} dF(t)$, $F(t)$ is the dependence of the transmission time of a data pack with jampack without overlay. $X^*(s) = \int_0^\infty e^{-st} dX(t)$, $X(t)$ is the distribution function of random delay in the jampack retransmission, in the event of conflict (overlay of jampacks from different nodes of the network); while $V_k^*(s) = \int_0^\infty e^{-st} dV_k(t)$, $V_k(t)$ is the dependence of the jampack transmission time and delay in confirmation transmission on the transmitted jampack from the *k*th node in case of conflict.

Then

$$P_k^*(s) = \sum_{n=1}^{\infty} (1 - g_k)^{n-1} g_k (X^*(s))^{n-1} \times$$
$$\times (V_k^*(s))^{n-1} F^*(s) = g_k F^*(s) \frac{1}{1 - (1 - g_k) X^*(s) V_k^*(s)} \quad (3)$$

Considering the properties of the Laplace–Stieltjes transform [16], expressions for moments $P_k^{(1)}$ and $P_k^{(2)}$ of distribution function $P_k(t)$ are easily obtained using differentiating expression (3) by *s*.

The methods for calculating the moments of distribution function $V_k(t)$ and $X(t)$ together with the necessary calculation formulas to evaluate the load of the transmission medium and network nodes are presented in [16].

The moments of distribution function $G_k(t)$ of the service time for a packet arriving at the *k*th node of the network are determined by the following formula:

$$G_k^{(1)} = P_k^{(1)} + W_k^{(1)}, \; G_k^{(2)} = P_k^{(2)} + 2P_k^{(1)} W_k^{(1)} + W_k^{(2)}, \quad (4)$$

wherein $W_k^{(1)}$ and $W_k^{(2)}$ are the moments of distribution function $W_k(t)$ of the waiting time for starting the packet transmission when it arrives at the free *k*th node of the wireless network [16].

Considering the Poisson character of packet streams arriving to the network nodes, the average waiting time of packets in the queue for service in the *k*th node $W_{\exp k}^{(1)}$ is determined by the Pollaczek–Khinchine formula [10], as follows:

$$W_{\exp k}^{(1)} = \frac{1}{2} \cdot \frac{\lambda_k G_k^{(2)}}{1 - \lambda_k G_k^{(1)}}. \quad (5)$$

The average packet service time $T_k^{(1)}$ allowing for the waiting time for starting the transmission in the network nodes is determined by the following expression:

$$T_k^{(1)} = W_{\exp k}^{(1)} + G_k^{(1)}. \quad (6)$$

As in [16], the probabilities of the on-time delivery of packets Q_k, arriving at the *k*th node of the wireless network are also defined by the following relations:

$$Q_k = \frac{h(1 - \lambda_k G_k^{(1)})}{h - \lambda_k + \lambda_k G_k^*(h)} G_k^*(h), \; k = \overline{1, N}, \quad (7)$$

where $h = 1 / T_{\text{dir}}^{(1)}$, $T_{\text{dir}}(t) = 1 - e^{-ht}$, $T_{\text{dir}}^{(1)}$ is the directive packet transmission time in the network.

$$G_k^*(h) = \frac{1}{\left(\frac{h}{y_k} + 1\right)^{x_k}}, \; x_k = \frac{(G_k^{(1)})^2}{G_k^{(2)} - (G_k^{(1)})^2},$$
$$y_k = \frac{G_k^{(1)}}{G_k^{(2)} - (G_k^{(1)})^2}. \quad (8)$$

Relations (8) can be easily established by approximating the distribution function $G_k(t)$ at two moments $G_k^{(1)}$ and $G_k^{(2)}$ by means of gamma distribution, while also considering the assumption that the constraint on the directive packet service time in the network $T_{\text{dir}}(t)$ is a random variable distributed according to the exponential law. The corresponding transformations are presented in [16].

The total intensity of the on-time served stream (network performance) is calculated by the following formula:

$$\lambda_{\text{sum}} = \sum_{k=1}^{N} \lambda_k Q_k, \quad (9)$$

where Q_k is determined by relation (7).

The method thus developed for evaluating the efficiency of wireless networks with the CSMA/CA access method forms the basis for implementing the computer-aided design systems for multi-purpose wireless networks. These include Wi-Fi and long-distance wireless networks using narrow-area antennas and CSMA/CA access method for communication.

4. MODELING THE WIRELESS NETWORK EFFICIENCY EVALUATION

A software package entitled "*The analytical modeling system for information transmission processes in networks*" has been developed for the general purposes of implementing the analytical model considered here. The aim is to evaluate the efficiency of networks with CSMA/CA access method in C++ language in the *Boland C++ Builder* object-oriented programming environment,

Initial data is entered from the display screen in the dialog mode according to the forms specified. Without leaving the modeling system, the operator is able to adjust the initial data and save the corresponding calculation results in text and graphic files.

The on-screen form for entering the initial data and outputting simulation results is shown in Fig. 1.

The software package enables the network bandwidth to be calculated for any given size of the wireless network with CSMA/CA and different placement of network nodes. The type of node placement can be random or deterministic. In deterministic placement, nodes can be located at the same distance from neighboring nodes (equidistant placement) or at different distances (non-equidistant placement). The packet transmission time constraint must be defined when entering initial data. The probability of delivering packets in less time than the directive one depends significantly on the constraint defined for the packet delivery time. The performance defined as the total on-time transmitted packet stream in the wireless network also depends significantly on the given packet delivery time constraints. Characteristics such as node and transmission medium load, as well as probabilistic and temporal characteristics (waiting time in queues, packet transmission time) do not depend on the constraints imposed on the transmission time. However, they certainly depend significantly on the transmission medium bandwidth, the number of nodes and their placement, the network size, the intensity of packet streams arriving at the wireless network nodes for service, the length of info packs, and time delays resulting from jampacks overlay. During modeling, the speed of signal propagation in the transmission medium is assumed to be equivalent to the speed of light.

The packet transmission in the wireless network with CSMA/CA is simulated, in order to demonstrate calculations of probability-time characteristics of packet delivery processes and wireless network performance using the developed analytical method. For modeling purposes, the following initial data was selected:

- the size of the wireless network with CSMA/CA is 500 m;
- the type of node distribution in the network is random;
- the number of nodes in the network $N = 100$;
- bandwidth is 100 Mbps;
- signal propagation speed is $3 \cdot 10^8$ m/s;
- maximum packet retransmission delay is 10 μs;
- jampack length is 32 bits;
- directive time is 0.005 s;
- info pack length is 1 Kbit;
- packet arrival rate is the same in all nodes.

It should be noted that the developed software package also enables modeling to be performed at different packet arrival rate at network nodes for service.

The calculation results for probabilistic and temporal characteristics, performance, load of nodes and transmission medium with the defined initial data at load change (change of intensity of packet streams arriving at the network nodes for service) are presented in Fig. 2–6.

Packet delivery time in a wireless network depends on the time of waiting for transmission in the queue at network nodes, as well as the time of packet transmission allowing for emerging conflicts. Therefore, the parameters of information processing in a wireless network should be selected in such a way that no bottlenecks, i.e., overloads of individual nodes and the transmission medium might occur within the entire range of changes in the intensity of the packet streams being processed in the system. In a balanced system, the load of the transmission medium and the load of the nodes when the load increases should be close to each other. As the network length decreases and the number of nodes decreases for a given transmission medium capacity, the length of the transmitted packets should increase in order to balance the network when the load increases.

When increasing the network size and the number of nodes at a given network bandwidth, in order to balance the network within the entire range of load changes, the length of transmitted information packets must be reduced. This will enable optimal performance under transmission time constraints, due to a reduced probability of conflicts.

Specific recommendations on selecting parameters and modes of operation for the wireless network can be obtained by conducting multivariate analytical calculations. This can be done by using the software package implementing the analytical method used for studying wireless networks with CSMA/CA access to the transmission medium.

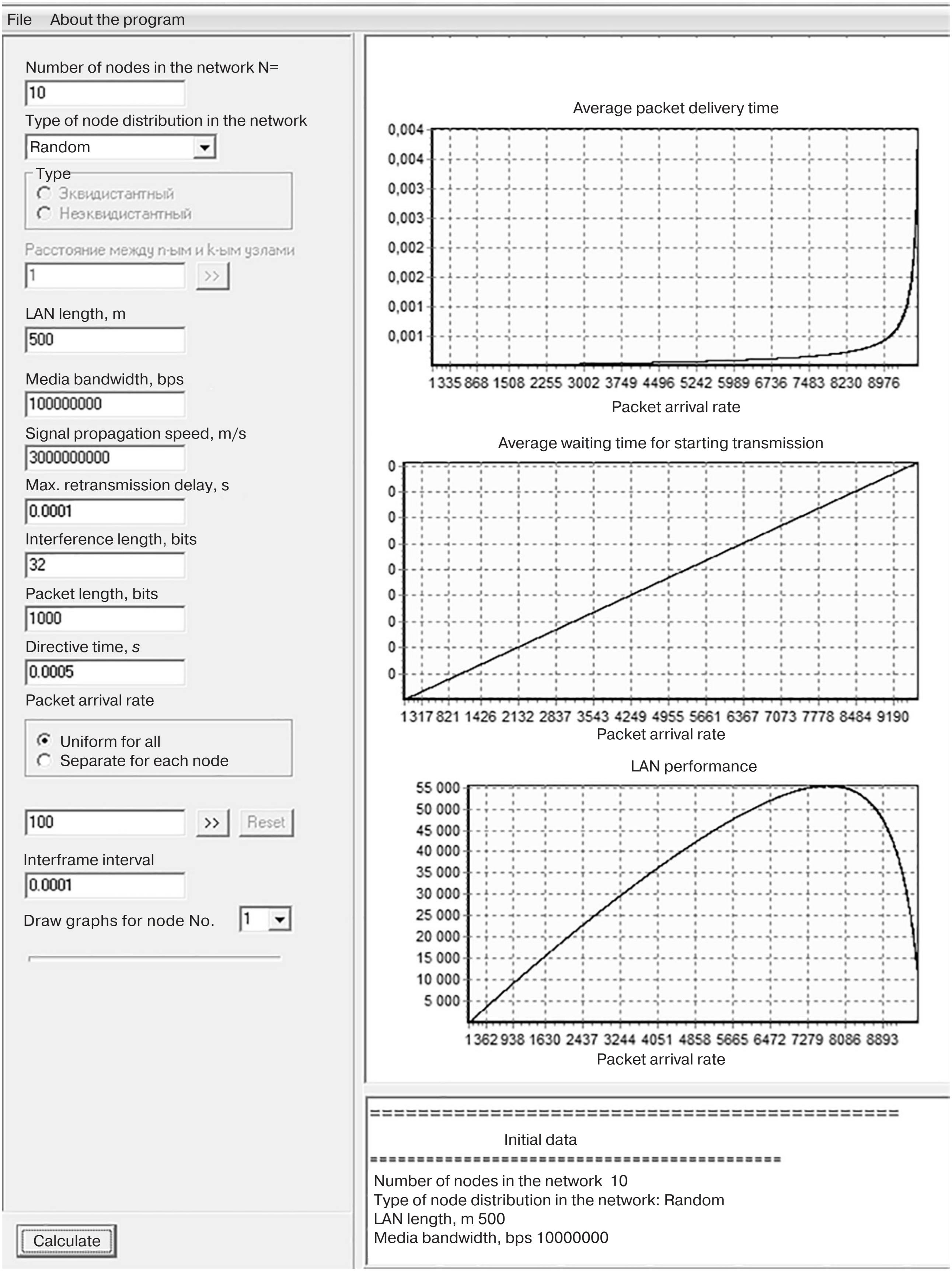

Fig. 1. The screen form for input/output of simulation results

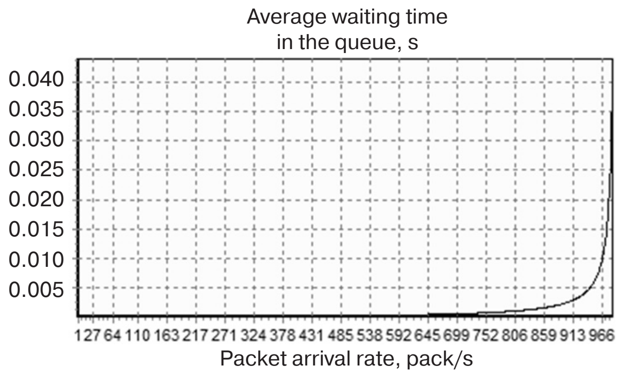

Fig. 2. Dependence of the average waiting time for packet transmission in nodes (s) on the packet arrival rate at the wireless network nodes and equal packet arrival rate at the network nodes

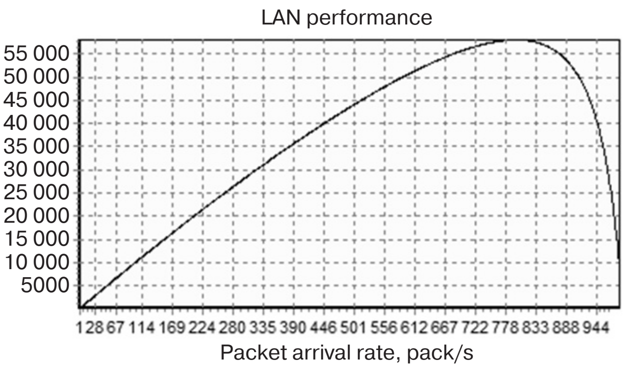

Fig. 3. Dependence of network performance on the packet arrival rate at the wireless network nodes at random node placement (N = 100), equal packet arrival rate at network nodes, and constraints on the packet delivery time

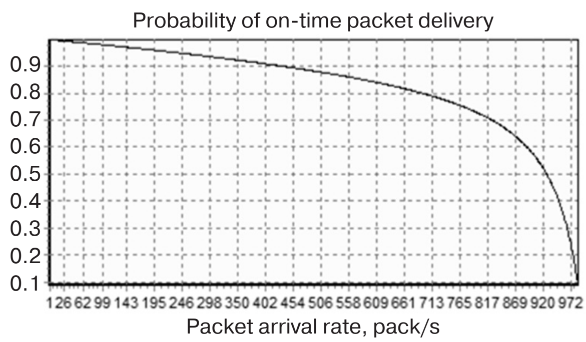

Fig. 4. Dependence of the probability of on-time packet delivery on the packet arrival rate of the wireless network nodes under random node placement (N = 100), equal packet arrival rate at network nodes, and packet delivery time constraint

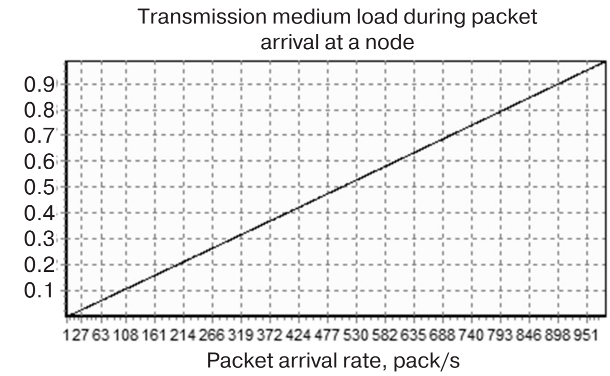

Fig. 5. Dependence of the transmission medium load during packet arrival at the node on the packet arrival rate at the wireless network nodes at random node placement (N = 100), and equal packets arrival rate at network nodes

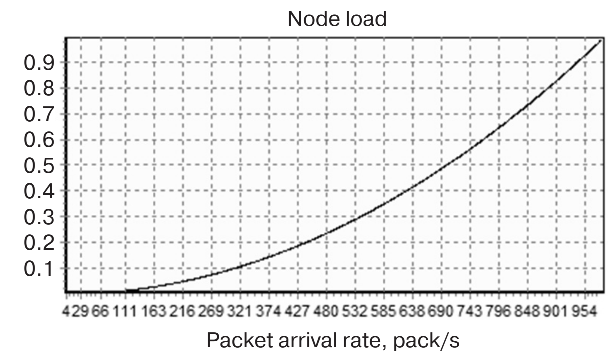

Fig. 6. Dependence of network node load on the packet arrival rate at wireless network nodes at random node placement (N = 100) and equal packet arrival rate at the network nodes

CONCLUSIONS

In this paper, the following main results were obtained.

Models used to analyze the probability-time characteristics of information processing in distributed information-computing systems were classified.

The paper also demonstrated the necessity of priority development of nested analytical models describing the processes of packet transmission under limitations on the time of information transmission in networks at the channel level.

Analytical formulas for evaluating time characteristics of packet transmission, node load, transmission medium load, and performance of wireless networks with CSMA/CA access method were established. Their operation is described by the IEEE 802.11 communication standard.

The software package is based on the developed analytical method. Use of the software allows the performance of wireless network and probabilistic and temporal characteristics of packet transmission at different transmission medium bandwidths and network sizes to be evaluated. It also provides an opportunity for multivariate analysis of different operating modes of wireless networks with CSMA/CA access method to be performed.

The description of the theoretical principles of the proposed analytical method for evaluating probabilistic and temporal characteristics and performance under the time constraint on information transmission in wireless networks with CSMA/CA is universal. It is used in the development of practical works in such disciplines as "Architecture of computing systems" and "Methods and means of protection of computer information" at the MIREA – Russian Technological University.

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

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About the authors

Alexander S. Leontyev, Cand. Sci. (Eng.), Senior Researcher, Associate Professor, Department of Mathematical Support and Standardization, Institute of Information Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: leontev@mirea.ru. RSCI SPIN-code 5798-9721, https://orcid.org/0000-0003-3673-2468

Dmitry V. Zhmatov, Cand. Sci. (Eng.), Docent, Associate Professor, Department of Mathematical Support and Standardization, Institute of Information Technologies, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: zhmatov@mirea.ru. Scopus Author ID 56825948100, RSCI SPIN-code 2641-6783, https://orcid.org/0000-0002-7192-2446

Об авторах

Леонтьев Александр Савельевич, к.т.н., старший научный сотрудник, доцент кафедры математического обеспечения и стандартизации информационных технологий, Институт информационных технологий ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: leontev@mirea.ru. SPIN-код РИНЦ 5798-9721, https://orcid.org/0000-0003-3673-2468

Жматов Дмитрий Владимирович, к.т.н., доцент, доцент кафедры математического обеспечения и стандартизации информационных технологий, Институт информационных технологий ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: zhmatov@mirea.ru. Scopus Author ID 56825948100, SPIN-код РИНЦ 2641-6783, https://orcid.org/0000-0002-7192-2446

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