An Approach Towards Automate Models Construction and Research of Wireless Local Area Networks based on State Transition Diagram

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Abstract: - Wireless Local Area Networks (WLANs) are widely used and their number is constantly increasing. Therefore, the creation of models for their detailed study, and even more, so the automation of this process is an urgent task. As an example of the research object, we chose the Media Access Control (MAC) sublayer and the Carrier Multiple Access with Collision Avoidance (CSMA/CA) access scheme. A simplified version of the state transition diagram was suggested by us, and an analytical model based on a system of differential equations was developed. Automation of the process of creating such models is realized by a software solution developed to automate the construction of analytical models of any objects described by a state transition diagram. The program automatically constructs and solves a system of differential equations using the substitution method, as well as constructs state diagrams.

Key-Words: - Wireless Local Area Network (WLAN), Media Access Control (MAC) sublayer, access to the physical environment, CSMA/CA scheme, State Transition Diagram, Mathematical model

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1 Introduction

One of the important tasks for the improvement of wireless communication is to increase the efficiency of wireless local networks and ensure the required quality of service. Wireless communication is developing rapidly, and at this stage, significant progress can be noted in increasing the transmission speed at the physical level of the network architecture. However, the physical environment of a Wireless Local Area Network (WLAN) is common to all its nodes, and special methods of organizing station access to the common environment divide this environment between active stations and require the use of certain significant resources, including time. As a result, even with the use of the most effective technologies at the physical layer, the efficiency of using wireless channels wants to be better. Therefore, the analysis and improvement of one of the bottlenecks of wireless local networks, the Media Access Control sublayer (MAC-sublayer), which is responsible for stations' access to the shared environment, is an urgent and important task. One of the ways to solve this problem is to develop models that will allow you to determine the characteristics of existing networks, analyze them, and develop ways to improve them.

Creating models for network analysis is a complex, highly intellectual, time-consuming task. Therefore, the development of an approach for automating the construction of models of a certain class is a significant contribution to the solution of this problem.

The main contributions of this paper can be summarized as follows:

- Automation building process analytical models of the Carrier Multiple Access with

Collision Avoidance (CSMA/CA) scheme and their investigation.

- Development of an approach to automating the construction of object models that can be described by a diagram of transitions with an arbitrary number of states, transitions, and their intensities.

2 Related Work

The current trend in the development of telecommunication technologies is aimed at increasing the use of wireless communication and the requirements for its quality. One of the main problems of wireless communication is the sharing of common physical environment resources between active participants. In Wireless Local Area Networks, the actual direction of research is the analysis and improvement of access methods to the physical environment.

There are several categories of access methods to the shared physical environment, the most common of which is the competition-based method. The competitive access method is used by such well-known standards as IEEE 802.11 for WLAN, [1], and IEEE 802.15.4 for low-speed wireless personal networks (Low-Rate Wireless Personal Area Networks, LR-WPAN), [2]. The access method described in these standards is implemented as Carrier Sense Multiple Access with Collision Avoidance. A lot of work has been devoted to the study and improvement of the CSMA/CA scheme. Some refer to the operation of the method in wireless local area networks, [3], [4], [5], [6], others in wireless sensor networks, such as, [7], and still others in wireless body area networks (WBAN), for example, [8].

Articles, [3], [5], can be used as an example of improving the CSMA/CA scheme for wireless local networks and illustrating the use of machine learning for these purposes. To increase the performance of the CSMA/CA scheme, reinforcement learning is used to optimize the value of the contention window by adapting to the traffic in the WLAN. As a result, the proposed access scheme has a higher throughput than the existing CSMA/CA scheme. In, [7], to improve the performance of non-slotted CSMA/CA, the authors propose a modified non-slotted CSMA/CA that divides the backoff delay into two components: main and additional. The analysis of the modified CSMA/CA was carried out using the Markov model, and the expressions for estimating the average delay, energy consumption, and reliability were obtained. The OPNET simulation package was applied to test the proposed Markov model and compare the modified method with the standard one. The results demonstrate that the modified CSMA improves reliability while reducing the average delay. Article, [9], proposes a modified CSMA/CA scheme that provides channel coordination between heterogeneous wireless technologies. Wi-Fi (IEEE 802.11) and Zigbee (IEEE 802.15.4) networks are used as WLAN and WPAN technologies. An important positive aspect is that the proposed method does not require modification of hardware and standards for either WLAN or WPAN. The paper, [9], proposes an improved Traffic Class Prioritization based on the CSMA/CA scheme for IEEE 802.15.4 Medium Access Control in intra-wireless Body Area Networks. The prioritized channel access is achieved by assigning a backoff period range to each traffic class in every backoff during contention. The main advantage of the proposed scheme is reduced packet delivery delay, packet loss, and energy consumption, and improved throughput and packet delivery ratio.

One of the current areas of improvement in wireless communication is the use of Quality of Service (QoS) mechanisms, both in mobile communication networks, [10], and in local networks, [4], [11]. To improve QoS in WLAN, in the work, [4], adaptive mechanisms for managing parameters of the CSMA/CA scheme are proposed, in, [11], for CSMA/CA was proposed a new model used a feedback-controlled method with fuzzy logic.

Various mathematical tools are used to study the MAC sub-layer, for example, Markov processes, [7], [10], [12], machine learning, [3], [5], and analytical and simulation modeling, [4], [5], [7]. They use both their developed programs, [4], and special tools, such as Network Simulator, OMNET+, OPNET, Graphical Network Simulator, Matlab/Simulink, Maple, CISCO Packet Tracer, and others.

The main modes of wireless local network operation at the MAC-sublayer are described in, [1]. In the paper, [6], a description of the operation of a wireless local network station is presented and a diagram of transitions between its states is given. This diagram has been described by a system of differential equations and, as a result, analytical expressions that allow estimating the probability of a WLAN station being in each of its possible states were defined, [13].

This paper proposes an approach for automating the model construction that describes, similar to [13], the MAC-sublayer of local networks using a system of differential equations. With this approach, a system of automated model construction based on transition state diagrams was developed. The relevance of such studies is confirmed by works on the automation of intellectual processes and the model's construction for other applications, [14], [15], [16], [17], [18].

3 Model of the CSMA/CA Scheme of IEEE 802.11 Standard

The state transition diagram of the CSMA/CA method of a wireless station when organizing frame sending includes the following set of states, [6]: idle state, non-Backoff carrier sensing state, Backoff state, collision state, successful transmit state, wait for acknowledge or receive negative acknowledge NAK state, and receive acknowledge (ACK) state.

After a successful transmission, the station by default must wait until the destination receives an ACK confirmation frame. During this interval, the station cannot perform new operations. Only after receiving the ACK frame, the station can proceed to the transmission of the next frame. Considering this, it is advisable and possible to simplify the model by combining the state of successful transmission and waiting for acknowledge state into one - the state of successful transmission and receipt of the ACK frame. Figure 1 shows a state transition diagram that implements this simplification.

The CSMA/CA state transition diagram has 6 states:

- 1 – idle state.
- 2 – non-backoff carrier sensing state.
- 3 – backoff (failure) state.
- 4 – collision state.
- 5 – wait for acknowledgment or receive NAK state.
- 6 – successful transmission and receiving ACK acknowledge the state

Compared to the original scheme described in [6], it lacks the successful transmission and acknowledgment waiting states, so it introduces one combined state as described above.

Let us denote by λ the intensity of the station's transition from one state to another. Then, following Figure 1:

- λ1 – the intensity of transition of the station transition from the idle state to the non-backoff carrier sensing state.
- λ2 – the intensity of the station transition from non-backoff carrier sensing state to backoff state.
- λ3 – the intensity of the station transition from the backoff state to the non-backoff carrier sensing state.
- λ4 – the intensity of the station transition from non-backoff carrier sensing state to collision state.
- λ5 – the intensity of the station transition from collision state to wait for acknowledge or receive NAK state.
- λ6 – the intensity of the station transition from wait for acknowledge or receive NAK state to backoff state.
- λ7 – the intensity of the station transition from the state of non-backoff carrier sensing state to the successful transmission and receive ACK acknowledge state.
- λ8 – the intensity of the station transition from the successful transmission and receive ACK acknowledge state to the non-backoff carrier sensing state.
- λ9 – the intensity of the station transition from the successful transmission and receive ACK acknowledge state to idle state.

If a random process characterized by discrete states and continuous time describes the system, then its mathematical model will be a system of differential equations, [12]. For the one shown in Figure 1 graph system can be written as:

$$\begin{cases} \frac{dP_1(t)}{dt} = -\lambda_1 P_1(t) + \lambda_9 P_6(t), \\ \frac{dP_2(t)}{dt} = -\lambda_2 P_2(t) - \lambda_4 P_2(t) - \lambda_7 P_2(t) + \lambda_3 P_3(t) + \lambda_1 P_1(t) + \\ \quad + \lambda_8 P_6(t), \\ \frac{dP_3(t)}{dt} = -\lambda_3 P_3(t) + \lambda_2 P_2(t) + \lambda_6 P_5(t), \\ \frac{dP_4(t)}{dt} = -\lambda_5 P_4(t) + \lambda_4 P_2(t), \\ \frac{dP_5(t)}{dt} = -\lambda_6 P_5(t) + \lambda_5 P_4(t), \\ \frac{dP_6(t)}{dt} = -\lambda_8 P_6(t) - \lambda_9 P_6(t) + \lambda_7 P_2(t). \end{cases} \quad (1)$$

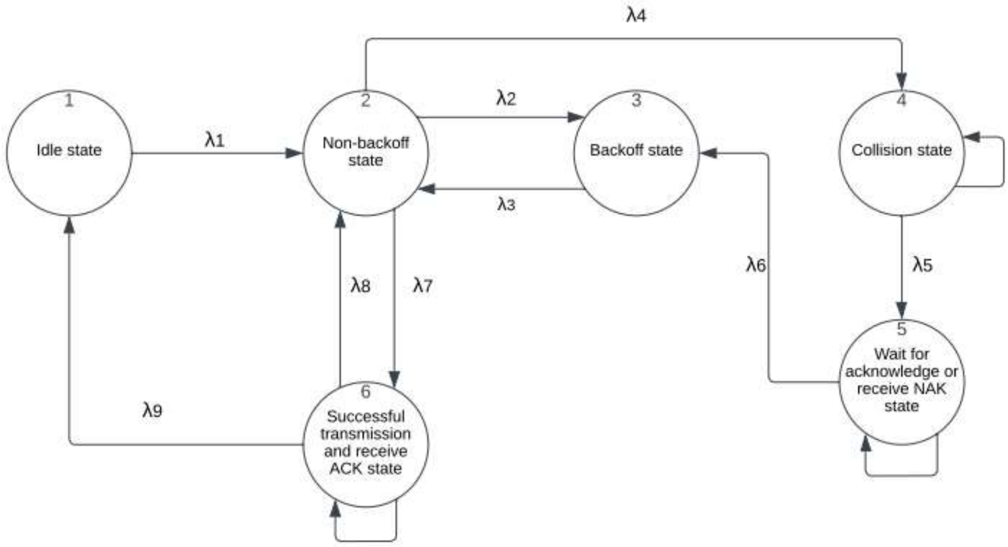

Fig. 1: Simplification state transition diagram for the CSMA/CA schema

To study the operation of the station in the stationary mode, the system of equations (1) can be rewritten in the system of algebraic equations:

$$\begin{cases} 0 = -\lambda_1 p_1 + \lambda_9 p_6, \\ 0 = -\lambda_2 p_2 - \lambda_4 p_2 - \lambda_7 p_2 + \lambda_3 p_3 + \lambda_1 p_1 + \lambda_8 p_6, \\ 0 = -\lambda_3 p_3 + \lambda_2 p_2 + \lambda_6 p_5, \\ 0 = -\lambda_5 p_4 + \lambda_4 p_2, \\ 0 = -\lambda_6 p_5 + \lambda_5 p_4, \\ 0 = -\lambda_8 p_6 - \lambda_9 p_6 + \lambda_7 p_2 \end{cases} \quad (2)$$

The total probability that the system is in any of the discrete states is equal to 1, which gives the normalization identity:

$$\sum_{k=1}^{6} p_k = 1 \quad (3)$$

To solve the system, we will use the method of substitutions and represent all probabilities through the probability p1.

From the first equation of system (2), the probability of the station being in the sixth state due to the probability p1 is deduced:

$$p_6 = \frac{\lambda_1}{\lambda_9} p_1 \quad (4)$$

From the sixth equation of system (2) considering equation (4):

$$p_2 = \frac{\lambda_8+\lambda_9}{\lambda_7} p_6 = \frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 \quad (5)$$

From the fourth equation of system (2) considering equation (5), we obtain the probability of being in the fourth state:

$$p_4 = \frac{\lambda_4}{\lambda_5} p_2 = \frac{\lambda_4}{\lambda_5}\frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 \quad (6)$$

From the fifth equation of system (2) considering equation (6), we get the probability of being in the fifth state:

$$p_5 = \frac{\lambda_5}{\lambda_6} p_4 = \frac{\lambda_5}{\lambda_6}\frac{\lambda_4}{\lambda_5}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 = \frac{\lambda_4}{\lambda_6}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 (7)$$

From the third equation of system (2) considering equation (7):

$$p_3 = \frac{\lambda_2}{\lambda_3} p_2 + \frac{\lambda_6}{\lambda_3} p_5 = \frac{\lambda_2}{\lambda_3}\frac{\lambda_1(\lambda_8+\lambda_9)}{\lambda_7\lambda_9} p_1 + \\ + \frac{\lambda_1\lambda_4(\lambda_9+\lambda_8)}{\lambda_3\lambda_7\lambda_9} p_1 = \frac{\lambda_1(\lambda_2+\lambda_4)(\lambda_8+\lambda_9)}{\lambda_3\lambda_7\lambda_9} p_1 \quad (8)$$

Substituting (4) - (8) into (3), we get the probability of the system being in any of the six states:

$$P_1 + \frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 + \frac{\lambda_1(\lambda_2+\lambda_4)(\lambda_8+\lambda_9)}{\lambda_3\lambda_7\lambda_9} p_1 + \\ \frac{\lambda_4}{\lambda_5}\frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 + \frac{\lambda_4}{\lambda_6}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9} p_1 + \frac{\lambda_1}{\lambda_9} p_1 = 1 \quad (9)$$

$$P_1 = 1/(1 + \frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} + \frac{\lambda_1(\lambda_2+\lambda_4)(\lambda_8+\lambda_9)}{\lambda_3\lambda_7\lambda_9} + \\ \frac{\lambda_4}{\lambda_5}\frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} + \frac{\lambda_4}{\lambda_6}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9} + \frac{\lambda_1}{\lambda_9}) \quad (10)$$

For simplification, we introduce the notation:

$$P_1 = 1/(1 + \frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} + \frac{\lambda_1(\lambda_2+\lambda_4)(\lambda_8+\lambda_9)}{\lambda_3\lambda_7\lambda_9} + \\ \frac{\lambda_4}{\lambda_5}\frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9} + + \frac{\lambda_4}{\lambda_6}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9} + \frac{\lambda_1}{\lambda_9}) \quad (11)$$

Stationary probabilities are determined by the formulas:

- The probability of the station being in an idle state:

$$p_1 = B \quad (12)$$

- The probability of the station being in a non-backoff carrier sensing state:

$$p_2 = \frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9}B \quad (13)$$

- The probability of the station being in a backoff state:

$$p_3 = \frac{\lambda_1(\lambda_2+\lambda_4)(\lambda_8+\lambda_9)}{\lambda_3\lambda_7\lambda_9}B \quad (14)$$

- The probability of the station being in a collision state:

$$p_4 = \frac{\lambda_4}{\lambda_5}\frac{\lambda_8+\lambda_9}{\lambda_7}\frac{\lambda_1}{\lambda_9}B \quad (15)$$

- The probability of the station being in wait for acknowledge or receive NAK state:

$$p_5 = \frac{\lambda_4}{\lambda_6}\frac{\lambda_9+\lambda_8}{\lambda_7}\frac{\lambda_1}{\lambda_9}B \quad (16)$$

- The probability of the station being in successful transmission and receiving ACK state:

$$p_6 = \frac{\lambda_1}{\lambda_9}B \quad (17)$$

The obtained analytical expressions (12)-(17) make it possible to estimate the probability of a WLAN station being in each of its states depending on the intensities of transitions between states.

4 Automatization of Creating a Model of the CSMA/CA Scheme

The analytical expressions obtained above in Chapter 3 are the results of a manual calculation. Since these calculations are time-consuming and cumbersome, and it is easy to make a mistake, it was decided to develop a program to automate the process of building analytical models based on the state transition diagram, which will greatly facilitate the process of building a system of differential equations and its solution using the substitution method. If you need to make any changes in the model, you won't have to do large-scale calculations manually. It will be done automatically in a few minutes with the program.

The developed program computes systems of algebraic equations by recognizing and converting textual data into numerical data. This program has several advantages over traditional methods of solving systems of algebraic equations.

First, it is more flexible and adaptive as it can work with textual data. Second, it is more accurate and efficient as it can recognize and convert textual data into numerical data.

This software solution can be used to automate the construction of analytical models of objects that can be described by a transition diagram with an arbitrary number of states, transitions, and different transition intensities.

The program allows you to describe the operation of the station as follows:

- Build a system of differential equations based on an arbitrary number of states and transitions with intensities between them.
- Obtaining analytical expressions representing the probability of the station being in each of its states as a function of the intensity of station transitions from each of its states to another using the substitution method.
- Build a diagram of state transitions with the possibility of editing.

The program works with intensities of transitions between states given in two ways: numerical intensities or intensities expressed by lambda expressions denoted by the letter L (Figure 2).

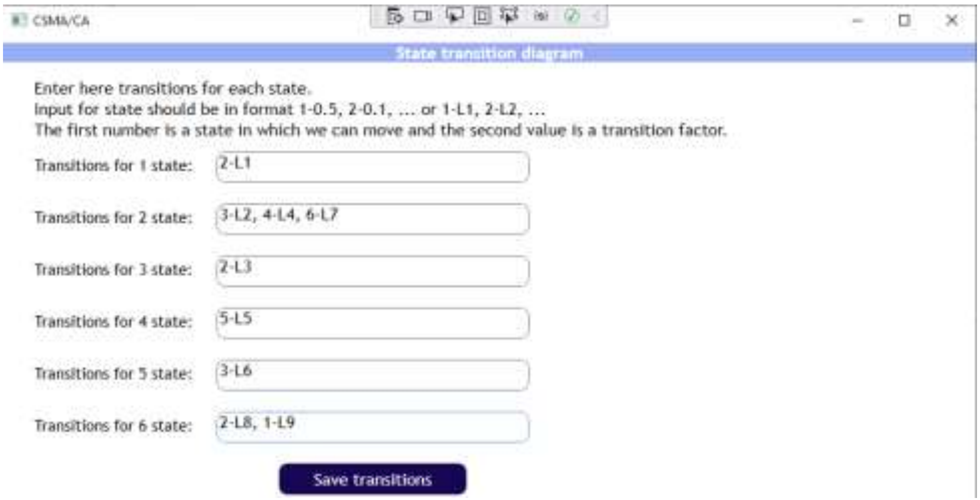

Fig. 2: User input for the calculation

Two data processing algorithms have been developed for this purpose: textual and numerical. For example, if a transition from the first state to the second is possible, then you need to set 2 - L1 or 2 - 1 (assume that the intensity of the transition from the first state to the second is 1), and the program will automatically use one of the calculation algorithms.

This possibility of entering intensities is quite convenient because for the first time, you can build a system of equations with intensities defined by lambda expressions, and in further calculations or experiments you can specify numerical intensities.

After introducing transitions between states, it is possible to redefine the intensity of transitions through L1, L2, ..., and Li. The proposed redefinition can be implemented in several ways: express Li in terms of Lk, use additional coefficients, or specify numerical values.

To implement the calculation of the system of algebraic equations, algorithms were developed for processing text data, their recognition, and conversion to numerical values for further processing and calculation of equations.

Since the program works with the intensities of transitions between states in two formats - numerical or symbolic with a lambda symbol, there was a need to correctly recognize and process the intensities of transitions entered by the user. Accordingly, it was decided to check whether the entered intensities contain text values. Depending on this, different data handler classes are used. It is also necessary to recognize mathematical operations entered in text format, especially in the case of redefining the intensities of transitions between states, which were initially determined directly through the lambda symbol. For this purpose, a text line analyzer was developed with the recognition of mathematical operators "+", "-", "*", and "/", considering the order of their processing and conversion into a numerical value.

In the process of calculations, the intensities of transitions determined by one parameter (number or coefficient) are determined first, and the intensities expressed by one mathematical operation are worked out in the next step. Then the intensities, which contain brackets, are calculated and the order of operations processing must be considered. Those transition intensities that contain equations with many parameters, such as L1 + k*(1 – L1 – m) + L2 + q, are worked out last.

The result of processing is analytical expressions representing the probability of the station being in each of its states (Figure 3). It also describes the transitions between the states of the station using the state transition diagram. Accordingly, p1, p2, p3, p4, p5, and p6 are the probabilities of being in each of the states.

The software product that automates the process of building analytical models of objects was developed using the C# programming language and the .NET 6 technology stack. Windows Presentation Foundation (WPF) was used as a platform for software product development – it is a user interface framework for developing Windows desktop applications. The user interface is designed using the declarative XAML markup language used in WPF. WPF was chosen for the development of the desktop application because it provides everything needed to create an innovative and functional user interface. WPF offers a wide range of tools and capabilities that allow us to create applications that look and perform great on any device.

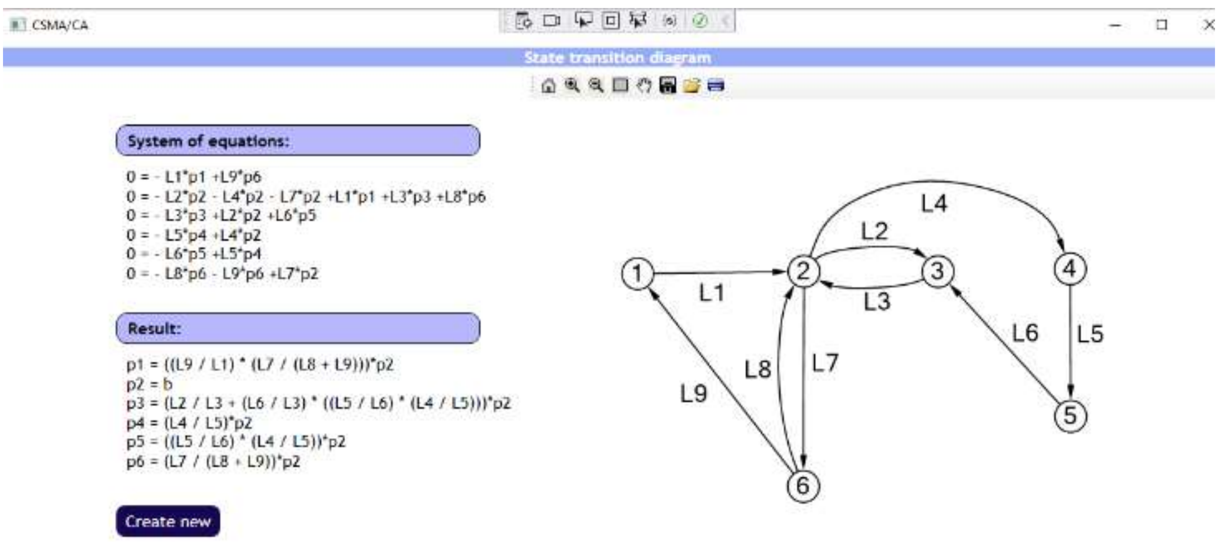

Fig. 3: Output of the program

Additionally, WPF is a relatively new platform, which means that it is constantly evolving and improving.

The program is a significant achievement in the field of computer programming. This software solution has the potential for wide application in a variety of disciplines, including education and science. For example, it can be used to solve systems of algebraic equations that occur in the school curriculum or to build analytical models of any objects described by a diagram of state transitions.

5 Conclusion

IEEE 802.11 wireless LAN station is considered a stochastic system, the operation of which depends on many random factors. It is noted that after a successful transmission, the station by default must wait until it receives an ACK confirmation frame from the destination and during this waiting interval, the station cannot start a new frame transmission.

Based on this, a simplified state transition diagram of the CSMA/CA method during the operation of a wireless LAN station in transmission mode is proposed. This proposed diagram is used for our further research.

First, we manually developed and presented an analytical model based on a system of differential equations for the proposed state transition diagram. Analytical expressions were obtained for the probabilities of the station being in all states. The resulting formulas can be used in further analysis and improvement of the CSMA/CA scheme.

Secondly, a software solution was developed for automating the construction of analytical models of any objects described by a diagram of state transitions. The program automatically builds and solves a system of differential equations using the substitution method, and constructs state diagrams. The program was tested on the example developed at the previous stage and showed its correctness.

The solution is universal and can be applied to different models, as it works with an arbitrary number of states and transitions between them. Also, for convenience, the intensity of transitions is worked out in two ways - numerical and symbolic (lambda expressions).

The developed program allows quick performing calculations and easy making of changes. It is also convenient to use for conducting experiments related to the changes in intensities to monitor the dependence of the intensity and the probability of staying in the corresponding state.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.