CSMA/CA Scheme Analysis: Case of One Node with Explicitly Predominant Network Load

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Abstract — The performance of wireless local and personal area networks is highly dependent on the physical medium access scheme implemented on the MAC sublayer of the network's architecture. Currently, the most common approach relies on a competition-oriented method known as carrier sense multiple access with collision avoidance (CSMA/CA). This paper studies the CSMA/CA scheme using a model based on a state transition diagram. The model is represented by a system of Chapman-Kolmogorov differential equations, which, in combination with the introduction of certain relationships between the intensities of transitions between different states, makes it possible to model the behavior of CSMA/CA in a network in the presence of a node with explicit predominant network load. We study the behavior of a network in which the output traffic of a station with a clearly predominant network load changes synchronously and proportionally to the total traffic of all active nodes. For this case, the asymptotic value of the probability of a successful transmission state does not depend on changes in the generated traffic. Any other traffic relations violate this property.

Keywords — CSMA/CA scheme, Chapman-Kolmogorov differential equations, performance evaluation of wireless networks

1. Introduction

The current development of telecommunication technologies is focused on increasing the use and performance of wireless communication [1]. One of the main problems of wireless communication is access to the shared physical medium, where the competition-based method is the most commonly used approach. Well-known standards such as IEEE 802.11 (WLAN) [2] and IEEE 802.15.4 (LR-WPAN) [3] support contention-based access method relying on the carrier sense multiple access with collision avoidance (CSMA/CA) scheme.

There are many works devoted to studying and improving massive and multiple access, including CSMA/CA. Each of them refers to limited applications, goals of a specific study, and uses a specific mathematical definition. Work [4] focuses on improving massive access to IoT gateways, while [5] is an example of a modification of the CSMA/CA scheme for wireless sensor networks. The authors of [4] propose a new traffic shaping method that significantly reduces the congestion at the gateway and improves overall performance of the IoT network. Article [5] modifies unslotted CSMA/CA, focusing on reliability and delay. The OPNET modeling tool is used for testing and comparing the modified method with the standard approach. The results demonstrate that the modified method improves reliability and reduces average delay.

In [6], an improvement of the CSMA/CA scheme for WLANs is proposed using machine learning, where the access point adjusts the value of the contention window according to the wireless traffic load. The proposed access scheme has a higher throughput than CSMA/CA. The authors of [7] propose a modified CSMA/CA approach which allows channel coordination among heterogeneous wireless technologies. Wi-Fi (IEEE 802.11) and ZigBee (IEEE 802.15.4) network standards are used as WLAN and WPAN technologies. As a significant advantage, the proposed method does not require any hardware or software modifications. Research [8] focuses on developing and testing a MAC protocol that utilizes CSMA/CA and incorporates a transform alignment technique to improve the bit error rate.

By integrating an enhanced CSMA/CA mechanism proposed in [9], collisions are reduced, channel assessment accuracy is improved, and energy consumption is mitigated, resulting in better overall network performance. In [10], an increase in network throughput of 35 – 40% was achieved, due to replacement the half-duplex mode of CSMA/CA operation with the full-duplex mode.

In [11], a VLAN model with a CSMA/CA protocol is presented to prevent virtual attacks and other network intrusions, while in [12], a dynamic back-off method for multi-node communication based on CSMA/CA is proposed. An improved antijamming technique for the CSMA/CA protocol that uses reinforcement learning is presented in [13].

Different works use various indicators to study and improve multiple and massive access. For example, the authors of [14] propose the use of logarithmic values of data transmis-

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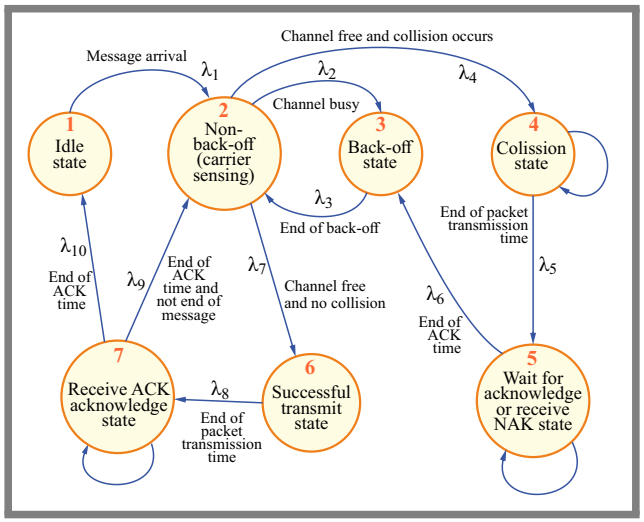


Fig. 1. CSMA/CA state transition diagram [20].

sion rates to adjust the modulation and coding scheme levels of data packets in CSMA/CA networks, while [15] and [16] focus on improving throughput and latency in wireless local area and sensor networks, and [17] focuses on energy efficiency in wireless sensor networks. In this paper, the probabilities of a network station being in different states during the operation of the CSMA/CA scheme are used as indicators.

This work studies the characteristics of the CSMA/CA scheme in wireless networks with an explicit predominance of the network load of one station. Attention is paid to the case of synchronous changes in the outgoing traffic of the active station, which may be characteristic for example, of Industrial IoT [18] and IoT applications [19].

The foundation of our work is [20], which investigates the CSMA/CA state transition diagram that we use as the core for the proposed approach. Article [20] presents an analytical model for calculating the performance of the MAC protocol in a wireless local area network, with a particular emphasis placed on normalized throughput and packet delay, and provides detailed numerical results, their analysis, and a comparison with the simulation data. To describe the CSMA/CA state transition diagram from [20], in [21], we proposed a model based on the Chapman-Kolmogorov differential equations.

The difference between studies [20], [21] and this work is that the previous papers do not investigate the specific case of the explicit predominance of the network load and do not establish the invariance of the asymptotic probability of successful transmission under proportional changes in the traffic of the studied station and its remaining counterparts. Here, we analytically establish this property and determine the conditions under which it holds. The main results of this work include the following:

- A method is developed to specify the network operating mode using the flow intensity ratio between the states of a specific network station.
- It is established that under the condition of outgoing traffic from a station with an explicitly dominant network load and total traffic from all other active nodes changing synchronously and proportionally, the asymptotic value of the probability of it being the node in a successful transmission state does not depend on variations in the generated traffic. Other changes in the outgoing traffic of any network station that is not similar to the node under study may lead to variations in the asymptotic value of the probability of successful communication.

Differential equations of the Chapman-Kolmogorov type are used to analyze the processes that occur at the MAC sublayer of local wireless networks.

The numerical results presented in this work have been obtained using the Maple 2024 computer algebra system Maple 2024 [22]. The numerical results are expressed using 3 digits.

2. Proposed Methods

The dominance of one station in the network in sending frames to the physical medium can occur when all other nodes are characterized by significantly less frequent requests for access to the physical medium. This case can be typical in the Internet of Things, the Internet of Everything, and drone swarms using communication relays. An analysis of throughput and delays in a network of drone swarms with a single master controller using CSMA/CA is described in [23]. In this case, the master controller can be considered as a station explicitly dominating outgoing traffic. To send data, drones must communicate with a head unit by winning the competition to obtain the channel with neighbor drones, as these are trying to transmit data as well.

The network's endpoints do not communicate directly with each other. Instead, they rely on an access point control device which first relays the frames exchanged by the endpoints through itself and then carries the total load of all end nodes, transmitting it to specific destinations. Second, the access point may act as a gateway and receive data from an external network, relaying them to the end devices. With a high load, this function will work properly only if, when attempting to transmit a frame, it diagnoses, in the vast majority of cases, that the environment is free of frame transmissions initiated by other stations. In this case, there will also be fewer conflicts between stations starting transmissions almost simultaneously.

The formulation of the considerations described above is based on a state transition diagram for CSMA/CA presented in [20]. We describe the restrictions and conditions by the ratio of the intensity of different states. A specific station is assigned a predominant load status by introducing relationships between the intensities of specific transitions between the states from the state diagram shown in Fig. 1. A detailed explanation of the original CSMA/CA state transition diagram can be found in [20]. Here, a brief description is provided for reference.

The transition diagram includes 7 states. A given station may be in one of them based on the time-dependent probability of

$P_i = P_i(t)$. There are 10 possible transitions between states, the intensities of which are denoted by λ_j. The running state is idle state 1. The station switches to it (with intensity λ_{10}) after being in state 7 – receive acknowledgment (ACK) after the end of ACK time. This occurs when a successful frame transfer is completed. The station enters state 2 (carrier sensing state) when a packet for transmission arrives (λ_1) from its upper layer, when back-off ends (λ_3), or when the end of ACK and not the end of the message occurs (λ_9).

Depending on the current state of the network, the station transits from state 2 to one of the three following states: successful transmit state 6 (λ_7), back-off state 3 (λ_2), or collision state 4 (λ_4). State 6 is the point of successful transmission, while state 5 means waiting for ACK or receiving a negative acknowledgment (NAK). The station enters this state, with intensity λ_5, from the collision state 4 and exits it, with intensity λ_6, into the back-off state 3. Furthermore, λ_8 is the transition intensity from state 6 of successful transmission to state 7 (receive ACK).

The CSMA/CA scheme described in this paper is modeled by a random process characterized by discrete states and continuous time. In [21], a mathematical model based on the state transition diagram is proposed, taking the form of a system of ordinary differential equations, the so-called Chapman-Kolmogorov equations. In this paper, we use this model to study the network in a partial case of the network load being explicitly predominated by one station. This, in turn, requires a formal description of the constraints imposed on the network as a whole. It is the use of the transition state diagram as the primary basis for modeling that allows us to describe these conditions through the ratio of transition intensities between different states.

A flag that the studied station is a node with an explicit dominance of the network load is that all other stations together occupy the physical medium for transmission for a time that is shorter or significantly shorter. This means, in our case, that the physical layer protocols of a station with an explicitly predominant network load, when checking the state of the physical medium before transmitting data, will rarely detect that the medium is busy, and the number of registered collisions will also be insignificant.

If λ_1 characterizes the intensity of frame transmission generated by the studied station, then λ_2 and λ_4 depend on the intensity of frame transmission by all other active stations within the network. Therefore, thanks to the intensity ratio of λ_1 and λ_2, and also λ_1 and λ_4, we can describe our case of explicit predominance of the load of one station over all others. To formally describe the ratio of the intensity of frames from the studied station and the rest of the network nodes, coefficients k and m are introduced, such as

$$k = \frac{\lambda_2}{\lambda_1}\ ,\ m = \frac{\lambda_4}{\lambda_1}\ ,\quad \text{with}\ \ k + m < 1\ . \tag{1}$$

The $k + m < 1$ constraint ensures that the intensity λ_7 remains positive. The k coefficient determines the part of the frames that could not be transmitted due to the busy channel, while m determines the part of the frames that collide with other frames during transmission attempts. This is possible when two or more nodes attempt to transmit frames simultaneously or nearly simultaneously. When checking if the medium is busy, all nodes sensed that it was free and began a transmission that, however, ended in a collision.

Under these conditions, the behavior of all other network nodes will be automatically taken into account and, most importantly, the total traffic from all other nodes will change synchronously with the traffic changes of the station dominating the network load. This behavior is common for networks in which the explicit dominance of the network load by the communication element is a component of the control system.

3. Modeling and Results

According to [21], the system of differential equations that describes the CSMA/CA scheme based on the state transition diagram shown in Fig. 1 takes the following form.

In vector notation $P = (P_1, \ldots, P_7)^*$, we have

$$P'(t) = \Lambda \cdot P(t)\ , \tag{2a}$$

with the coefficient matrix

$$\Lambda = \tag{2b}$$

$$\begin{pmatrix}
-\lambda_1 & \circ & \circ & \circ & \circ & \circ & \lambda_{10} \\
\lambda_1 & -(\lambda_2+\lambda_4+\lambda_7) & \lambda_3 & \circ & \circ & \circ & \lambda_9 \\
\circ & \lambda_2 & -\lambda_3 & \circ & \lambda_6 & \circ & \circ \\
\circ & \lambda_4 & \circ & -\lambda_5 & \circ & \circ & \circ \\
\circ & \circ & \circ & \lambda_5 & -\lambda_6 & \circ & \circ \\
\circ & \lambda_7 & \circ & \circ & \circ & -\lambda_8 & \circ \\
\circ & \circ & \circ & \circ & \circ & \lambda_8 & -(\lambda_9+\lambda_{10})
\end{pmatrix}$$

depending on all the intensities λ_j and with initial state $P(0)$. Due to the structure of the system, as explained in the sequel, the sum of probabilities $P_i(t)$ is constant as required, thus we have:

$$\sum_{i=1}^{7} P_i(t) \equiv \sum_{i=1}^{7} P_i(0) = 1\ . \tag{2c}$$

P_i is the probability of the wireless node being in its 7 possible states. The system depends on 10 positive parameters λ_j, representing the intensities for the transition from one state to another.

We do not impose additional constraints on the values that the probabilities of nodes are in all its states at time $t = 0$. Introducing such constraints would make the proposed model non-compliant with real processes.

Since the process occurring in the network lasts for a long time, it is advisable to limit the behavior of the probabilities $P_i(t)$ as t tends to infinity, in which the final (limiting) probabilities of the states do not depend on the state in which the system was at the initial moment. A limiting stationary regime is established in the network, in which it passes from state to state, but the probabilities of the states P_i no longer change over time.

The system of differential Eqs. (2a), (2b), together with an initial condition as given in Eq. (2c) at $t = 0$, describes a CSMA/CA scheme of a wireless station and is used to study the operation of a wireless network in the scenarios considered.

3.1. Mathematical Properties

The mathematical properties and asymptotic behavior of the system given by Eq. (2) are as follows. The sum of rows of the matrix Λ in Eq. (2b) is zero, which implies

$$\sum_{i=1}^{7} P_i'(t) \equiv 0$$

and relation (2c).

For non-negative initial values $P_i(0)$, all solution values $P_i(t)$ also remain non-negative. This relation comes from the theory of logarithmic norms for differential equations in the following way:

$$\sum_{i=1}^{7} |P_i(t)| \leqslant \sum_{i=1}^{7} |P_i(0)| \quad \text{for all } t > 0 \,. \tag{3}$$

For the 1-vector norm

$$\|P\|_1 = \sum_{i=1}^{7} |P_i|$$

the associated logarithmic matrix norm evaluates to zero

$$\mu_1(\Lambda) = \max_j \left(\Lambda_{jj} + \sum_{i \neq j} |\Lambda_{ij}|\right) = 0 \,,$$

and this implies [24]:

$$\|P(t)\|_1 \leqslant \exp(t\,\mu_1(\Lambda)\,\|P(0)\|_1 = \|P(0)\|_1 \,.$$

In our case

$$P_i(0) \geqslant 0 \;\;, \;\; \sum_{i=1}^{7} P_i(0) = 1 \,,$$

hence

$$\sum_{i=1}^{7} |P_i(t)| \leqslant 1 \,.$$

Therefore, the occurrence of some $P_i(t) < 0$ would contradict relation (2c), i.e., our system indeed describes nonnegative values $P_i(t) \geqslant 0$.

The above argument can be applied to the unit vectors, i.e., for

$$P(0) = e^{(j)} \; (e_k^{(j)} = \delta_{j,k}) \,.$$

Then, with the solution operator (matrix exponential) $S(t) = e^{t\Lambda}$ we have $P(t) = S_j(t)$, where j is the column of $S(t)$. Therefore

$$S_{i,j}(t) \geqslant 0 \quad \text{for } i, j = 1, \ldots, 7 \,,$$

$$\sum_{i=1}^{7} S_{i,j}(t) = 1 \;\; \text{for } \; j = 1, \ldots, 7 \,.$$

$S(t)$ is the so-called *column-stochastic matrix*. For a small time, increment Δt

$$P(t) \mapsto P(t + \Delta t) = S(\Delta t)\, P(t)$$

represents the corresponding discrete-time stochastic process.

According to [21], a stationary state $P = P_{(\text{stat})}$ of Eq. (2a) is unique up to a multiplicative constant. For a unique particular value of this constant (depending on the λ_j) we obtain a stationary state with

$$P_i \geqslant 0, \; i = 1, \ldots, 7$$

and

$$\sum_{i=1}^{7} P_i = 1 \,.$$

In the terminology of linear algebra, the rank of the matrix Λ is 6 and it has the eigenvalue $\varepsilon = 0$. The stationary state $P_{(\text{stat})}$ is a corresponding eigenvector (kernel vector) of the matrix Λ.

For such a structure of the matrix Λ, all other eigenvalues $\varepsilon \neq 0$ have a negative real part, which comes from the Gershgorin theorem [25]. For the asymptotic behavior with increasing t, if

$$P(0) = P_{(\text{stat})} + \Delta(0)$$

then

$$P(t) = P_{(\text{stat})} + \Delta(t), \;\; \text{with } \; \Delta(t) \to 0 \;\; \text{for } t \to \infty \,.$$

This shows that the system defines an asymptotically stable process converging to the stationary state, independent of the initial distribution satisfying

$$\sum_{i=1}^{7} P_i(0) = 1 \,.$$

The performance of a network that operates using the CSMA/CA scheme depends on the number of active nodes, the outgoing traffic generated by each network station, and the distribution of this traffic over time.

During transmission, the wireless station using the CSMA/CA scheme at the MAC sublayer is affected by internal and external factors. The main internal factor is the flow of IP data packets which the MAC sublayer receives from the superordinate network layer. The intensity of this flow determines the value of λ_1. The higher λ_1, the more requests the MAC sublayer has to be processed, the more frames need to be transmitted, and a wider bandwidth is required for transmission.

Therefore, the intensity λ_1 of the outgoing traffic of the node is one of the most important parameters of the model. It determines network performance, such as throughput and delay, which are most important to users.

The other parameters of the CSMA/CA scheme, such as the size of the competition window, the presence or absence of collisions, also depend on the outgoing traffic intensity λ_1, which is the main factor determining the parameters of the CSMA/CA scheme.

In the context of the state diagram shown in Fig. 1, the intensities $\lambda_j, j = 1, \ldots, 10$ have the following meaning:

- λ_1 – intensity of station's outgoing traffic,
- λ_2 – intensity of transition from carrier-sensing state to back-off state,

- λ_3 – intensity of transition from back-off state to carrier sensing state,
- λ_4 – intensity of transition from carrier-sensing state to collision state,
- λ_5 – intensity of transition from collision state to waiting for ACK or receiving NAK state,
- λ_6 – intensity of transition from waiting for ACK or receiving NAK state to back-off state,
- λ_7 – intensity of transition from carrier sensing state to successful transmit state,
- λ_8 – intensity of transition from successful transmit state to receiving ACK state,
- λ_9 – intensity of transition from receiving ACK state to carrier sensing state,
- λ_{10} – intensity of the transition from the receiving ACK state to idle.

In this study, the parameter λ_1 is of particular importance, since an additional condition, i.e., synchronous change in the outgoing traffic from the active nodes, is imposed thereon.

External factors include the outgoing traffic of other active network stations, their intensity, and distribution. The second external factor is interferences leading to errors in received symbols and generating additional traffic caused by the need to retransmit corrupted frames.

The purpose of the operation of the network is to transmit outgoing traffic from all nodes. Outgoing traffic from the stations is considered as a useful component of the total network traffic. However, in the presence of interference, the total network traffic also contains a redundant component, coming from retransmission cause by errors.

In wireless communication channels, the level of such interference can be significant. Data link layer protocols continuously monitor the received frames, and if an unrecoverable error is detected, such a frame is retransmitted. It is obvious that repeated frames increase total network traffic. A repeated frame, like all other frames, will compete for access to the medium according to the CSMA/CA, thus increasing the channel busy time and the probability of collisions. The CSMA/CA method does not distinguish between the original frame and its repetition, and accordingly does not create different access conditions.

Therefore, in the proposed model, there is no need to consider repeated frames as a separate class. They are integrated into the model as part of the outgoing traffic from the network nodes.

External factors that affect a given network station are the intensity of the output traffic intensity λ_1 of other network nodes, which together with the output traffic of the internet station, determine the intensities λ_2 and λ_4 of its transition from the carrier sensing state to the back-off state and the collision state, respectively.

The most preferred transition is from the carrier-detection state to the successful-transmission state, with a transition intensity of λ_7. It occurs only when there is a free channel for frame transmission and the transmitted frame did not collide, during its transmission, with other frames that could have been sent simultaneously.

In our case, a set of input data for studying the CSMA/CA method is the set of flow intensities λ_1, λ_2, and λ_4, since these parameters determine the behavior of the nodes. With an explicit dominance of the network load assigned to the main node, it is important to consider the ratio of λ_2 and λ_4 to λ_1. This is because λ_2 and λ_4 are integrated features of the network load of all other nodes. In particular, we set:

$$\begin{aligned} \lambda_2 &= k\,\lambda_1\,, \\ \lambda_4 &= m\,\lambda_1\,, \end{aligned} \tag{4a}$$

with $k + m < 1$.

Furthermore, the following relations are assumed:

$$\begin{aligned} \lambda_7 &= \lambda_1 - \lambda_2 - \lambda_4\,, \\ \lambda_5 &= \lambda_4\,, \\ \lambda_6 &= \lambda_4\,, \\ \lambda_3 &= \lambda_2 + \lambda_6\,, \\ \lambda_8 &= \lambda_7\,, \\ \lambda_9 &= j\,\lambda_7\,, \\ \lambda_{10} &= (1-j)\lambda_7\,, \end{aligned} \tag{4b}$$

with $0 \leqslant j < 1$.

The system matrix Λ is a multiple of λ_1, constituting its eigenvalues and this means that the speed of asymptotic convergence towards $P_{(\text{stat})}$ increases exponentially with λ_1. The stationary state $P_{(\text{stat})}$ evaluates to

$$P = P_{(\text{stat})} = c\left((1-k-m)(1-j), 1, 1, 1, 1, 1, 1\right)^*\,, \tag{5}$$

depending on the values of $k + m$ and j and independently of λ_1, with constant

$$c = \frac{1}{6 + (1-k-m)(1-j)}\,. \tag{6}$$

Equation (5) is the foundation of this paper, since, by setting the k, m and j constants, we fix the relationship between the traffic of the network nodes.

Consider the following example, assuming $k = m = 0.1$ and $j = 0$, then according to Eq. (6), $c = 0.147$, while by Eq. (5), the stationary value that the probability of a station is in successful transmission state is $P_{6(\text{stat})} = 0.147$ (independent of λ_1).

In Figs. 2 and 3 the dependence of the asymptotic stationary states depending on $k + m$ is illustrated for the case with $j = 0$.

Our goal was to investigate performance under the condition that the network load of one station is explicitly dominant and the summary output streams of all other stations varies synchronously therewith. To begin with, in order to obtain data for comparing the results of subsequent studies, we consider an example in which the probabilities of a station being in different states are determined for some predefined specific set of input data.

Let us recall the meaning of the probabilities $P_i(t)$ of the states of our station (see Fig. 1). These represent:

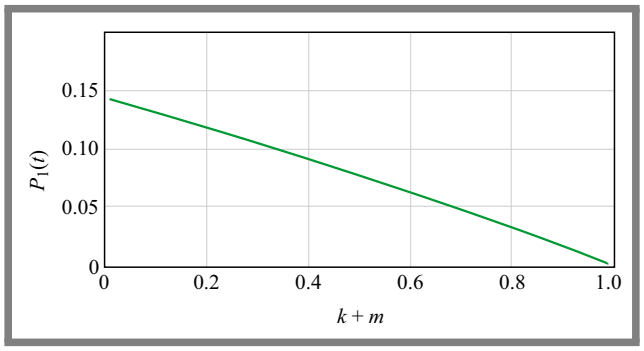


Fig. 2. Stationary probability P_1 depending on $k+m$.

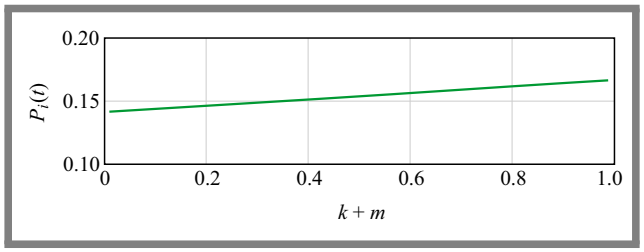


Fig. 3. Stationary probabilities $P_2 = \ldots = P_7$ as a function of $k+m$.

- $P_1(t)$ – idle state,
- $P_2(t)$ – non-back-off (carrier sensing) state,
- $P_3(t)$ – back-off state,
- $P_4(t)$ – collision state,
- $P_5(t)$ – waiting for ACK or receiving NAK,
- $P_6(t)$ – successful transmission state,
- $P_7(t)$ – receive ACK state.

3.2. Case Study

Equation (2) allows us to obtain a probabilistic estimate of the station operation in data transmission mode with respect to time t and then the probabilities for $k = m = 0.1$ and $j = 0$ are as follows

$$P_1(0) = 1 \text{ and } P_2(0) = \ldots = P_7(0) = 0\,.$$

From Eq. (5) the corresponding asymptotic state independent of λ_1 is

$$P_{\text{stat}} = (0.118, 0.147, 0.147, 0.147, 0.147, 0.147, 0.147)^*\,.$$

Figure 4 shows the evolution of all states over time for the case $\lambda_1 = 1$, allowing to estimate the ratios. Furthermore, recall that the dynamics increases with λ_1, i.e., for larger values of λ_1 the asymptotic state is approached more quickly.

Figure 5a shows that the probability $P_1(t)$ of idle state decreases significantly in t to its asymptotic value. When a new packet arrives, the station transits to non-back-off (carrier sensing) state 2. The probability $P_2(t)$ is shown in Fig. 5b. Depending on whether the physical environment is busy or not, the station turns either to back-off state 3 or to data transmission, respectively. The probability $P_3(t)$ is shown in Fig. 5c. When a station transmits data, there are two possibilities. In one of them, data transmission is successful (state 6). The probability $P_6(t)$ of successful transmission state is shown in

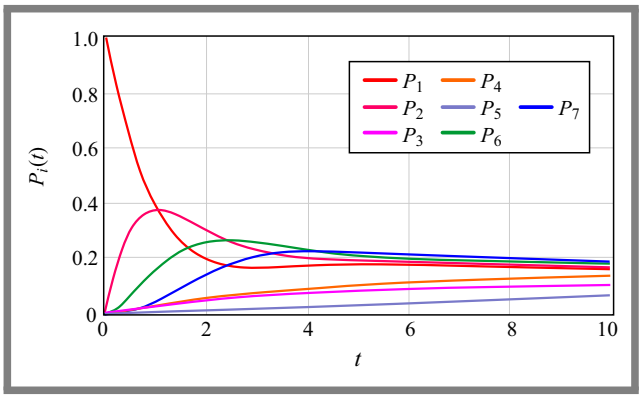


Fig. 4. Probabilities $P_i(t), i = 1, \ldots, 7$, for $\lambda_1 = 1$ and $k = m = 0.1$, $j = 0$.

Fig. 5e. From state 6, the station moves to state 7 (receiving ACK), the probability $P_7(t)$ of which looks similar to that shown in Fig. 5a. Due to the collision, the station passes to collision state 4, and then to state 5 of waiting for ACK or receiving NAK. The probability $P_4(t)$ of collision state 4 is shown in Fig. 5d.

3.3. Synchronous Change of Network Load

To study in detail the impact of flow intensity λ_1 on the operation of the station, we consider two scenarios:

- Scenario A, when all network stations change their traffic proportionally and equally,
- Scenario B, which involves deviation from synchronicity.

The asymptotic value $P_{6(\text{asy})} = P_{6(\text{stat})}$ for large values of the variable t is chosen for comparison.

The examination of scenario A assumes that if the traffic generated by the main station varies, the traffic of all other network nodes changes in the same proportion. In other words, k and m from Eq. (4a) remain constant. The part of the traffic of the studied station within in the total network traffic remains stable.

For example, for $k = m = 0.1$, according to Eq. (5) we obtain the asymptotic value $P_{6(\text{asy})} = 0.147$ that is independent of the intensity λ_1. This indicates that the CSMA/CA scheme, which operates on all nodes of the network, provides the same share of total bandwidth resources, while synchronous load changes.

Since scenario B does not introduce any constraints on the behavior of the λ_1 flow, the changes in the intensity λ_1 of all other nodes are independent and may differ from the variations in λ_1 at the station of interest.

The parameters k and m describe the impact of network traffic on the main station. The variations in network traffic are modeled by changing these values – higher values mean a heavy load. The distributions of traffic in the network correspond to different ratios between k and m. To demonstrate the changes in the probability $P_{6(\text{asy})}$ in scenario B for the general case, the coefficients k and m are varied from 0.1 to 0.8 in steps of 0.1. According to Eqs. (5), (6), the asymptotic value $P_{6(\text{asy})}$ for $j = 0$ depends on the sum $k+m$ and ranges

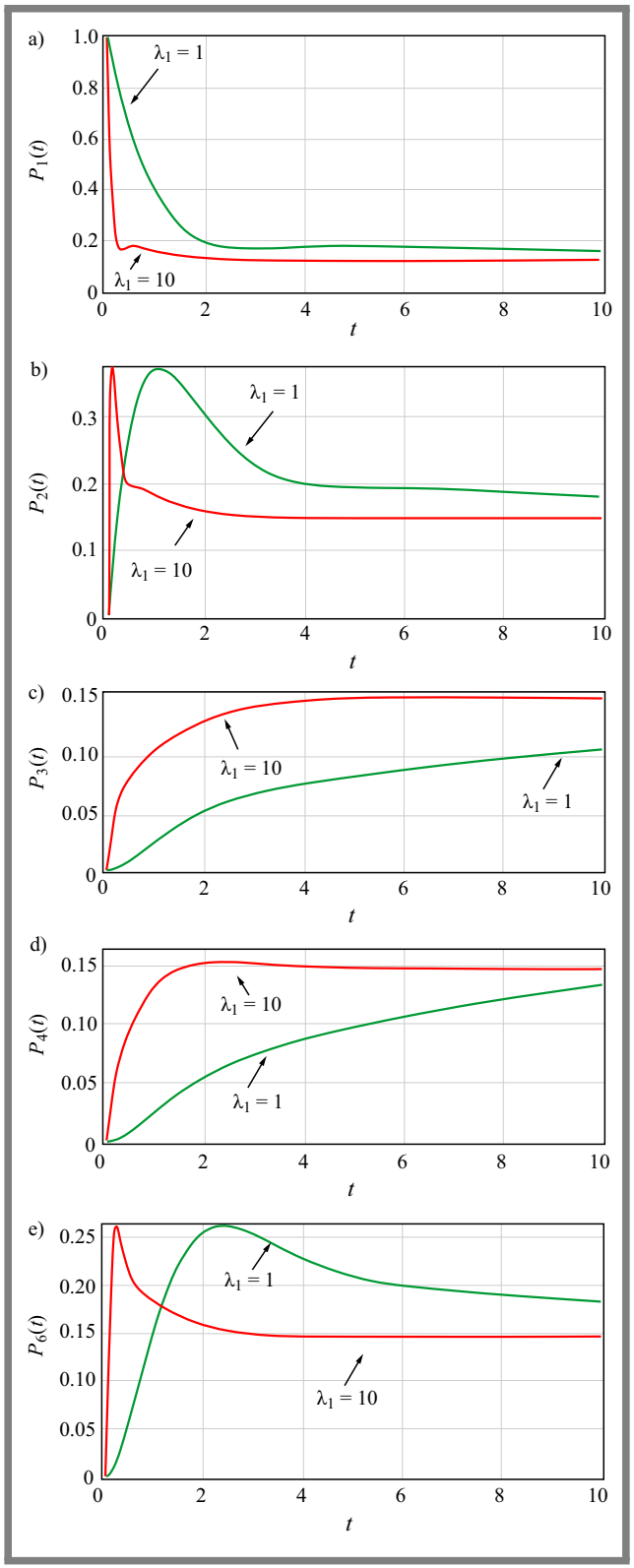


Fig. 5. Probability curve for $k = m = 0.1$ and $j = 0$: a) $P_1(t)$ (idle), b) $P_2(t)$ (non-back-off), c) $P_3(t)$ (back-off), d) $P_4(t)$ (collision), and e) $P_6(t)$ (successful transmission).

within the interval from 0.142 to 0.167 – see Fig. 3 and Tab. 1.

Data for the considered case for more realistic values of m are presented in Tab. 2.

Tab. 1. Results for scenario B – $P_{6(\text{asy})}$ versus $k + m$.

$k+m$	$P_{6(\text{asy})}$	$k+m$	$P_{6(\text{asy})}$
0.2	0.147	0.6	0.156
0.3	0.149	0.7	0.159
0.4	0.152	0.8	0.161
0.5	0.154	0.9	0.164

Tab. 2. Results for scenario B – $P_{6(\text{asy})}$ for practical cases of k and m.

$k \setminus m$	**0.02**	**0.04**	**0.06**	**0.08**	**0.10**
0.1	0.145	0.146	0.146	0.147	0.147
0.2	0.147	0.148	0.148	0.149	0.149
0.3	0.150	0.150	0.151	0.151	0.152
0.4	0.152	0.152	0.153	0.153	0.154

These results indicate that the CSMA/CA scheme is equally affected by the occupancy of the channel due to data transmission by other nodes k, as well as channel occupancy due to collision m, which occurs when frames are transmitted simultaneously or almost simultaneously by one or more stations.

4. Comparison and Discussion

To evaluate the CSMA/CA scheme, a model based on the transition state diagram and implemented by the Chapman-Kolmogorov system of differential equations was used. The simulation results in the form of probabilities $P_1(t)$ of the station being in the idle state, $P_2(t)$ of non-back-off (carrier sensing) state, $P_3(t)$ of back-off state, $P_4(t)$ of collision state, and $P_6(t)$ of successful transmission state are shown in Fig. 5. These probabilities characterize the CSMA/CA scheme and can be used, for example, to develop adaptive algorithms for controlling access to the physical environment.

In the discussion, it is advisable to consider only such effects which can be reasonably proven to be correct, and therefore also multiply indistinguishably from the other results. In all the considered cases, the output traffic of the main station always exceeds the total output traffic of all other nodes.

The input variables used in the experiments were the outgoing traffic intensity λ_1 of the network station under study and the intensities λ_2 and λ_4 of the transition from the carrier sensing state to the backoff state and to the collision state, respectively. By changing their values, we set different network operation modes. Other values of the transition intensity are derived from λ_1, that is, from the traffic generated by the node.

The higher the probability that a station is in a state of successful data transmission, the better the overall network performance. Therefore, the probability P_6 of the station being in a successful transmission state was chosen as the resulting model metric.

The total traffic in the network affects indicators such as channel occupancy and frame collisions. In the model considered, changes in total traffic of all nodes, except the one under study, are specified using coefficients k and m, which bind them to the output traffic of the station of interests. Scenario B does not impose restrictions on the values of the coefficients k and m, as well as the ratio between them, while scenario A keeps the values constant.

Scenario A shows that the output flow of a station with a clearly dominant output traffic and the total network traffic of all other stations change synchronously and proportionally to each other. The asymptotic value of the probability of successful transmission of a station does not depend on the changes in traffic generated by such a node. This proves that with synchronous changes in node loads, the CSMA/CA maintains the established resource distribution within the network.

Scenario B indicates that even with unchanged output traffic λ_1 of the main station, variations in the total network load achieved by different values of k and m, impact the operation of the station under study. This is illustrated in Fig. 5e.

Comparing the results for both scenarios, one may notice that if the change in the flows generated by the stations occurs synchronously and proportionally to each other, the asymptotic value of probability P_6 remains unchanged.

This dependance may be used for the development of adaptive control algorithms at the MAC-layer to improve the efficiency of local area networks [26], [27], in particular body area networks [28] or to develop tools to provide quality services under the IEEE 802.11 CSMA/CA protocol [29], as well as to improve communication in IoT environments [30].

5. Conclusions

Based on the description of a state transition diagram of the CSMA/CA scheme, the probabilities of the wireless station were found in all states encountered while operating in the transmission mode. The probability that a given node is in a successful transmission state was chosen as an indicator for the analysis of the CSMA/CA scheme.

The intensity of the outgoing traffic of network stations was used as a variable, the influence of which was studied considering two cases: the first one did not impose restrictions on the behavior of the outgoing network traffic, the other assumed the case when the outgoing traffic of network stations changes synchronously and proportionally to each other.

The results show that when the traffic of all active stations changes synchronously and proportionally, the asymptotic probability of finding the station in a successful transmission state does not depend on changes in the generated traffic. Under other conditions, this property does not hold. The results obtained can be useful, for example, for networks that control certain processes, as a change to their parameters leads to the generation of traffic by all controlling stations.

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