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Halim Khujamatov
Tashkent University of Information Technologies, kh.khujamatov@gmail.com

Ernazar Reypnazarov
Tashkent University of Information Technologies, reypnazar0vernazar@gmail.com

Doston Hasanov
Tashkent University of Information Technologies, dhasanov0992@gmail.com

Elaman Nurullaev
Tashkent University of Information Technologies

Shahzod Sobirov
Tashkent University of Information Technologies

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EVALUATION OF CHARACTERISTICS OF WIRELESS SENSOR NETWORKS WITH ANALYTICAL MODELING

Khujamatov Kh.E., Reypnazarov E.N., Khasanov D.T., Nurullaev E.E., Sobirov Sh.O.

Abstract: In this paper, a mathematical model of the operation process of the ZigBee standard wireless network for remote monitoring systems based on the Markov chain apparatus was developed. Using the model was evaluated of the operation process of the CSMA/CA algorithm of the MAC level of the IEEE 802.15.4 ZigBee standard. The peculiarity of this mathematical model is that it takes into account the level of loading of network elements and potential distortions in the transmitted packets as a result of the influence of interference. Using the developed mathematical model, the main characteristics of the network operation process, such as dependence of the probability of successful transmission of packets on the system load (on the number of nodes), the dependence of the bandwidth on system load (on the number of nodes) for the case where there is noise in the channel and for the absence of noise in the channel were obtained.

Keywords. ZigBee, IEEE 802.15.4, CSMA/CA, characteristic, model, router, coordinator.

Introduction

The sources of power supply of telecommunication stations are territorially distributed objects with a multi-level management hierarchy and a large number of structural units. In this regard, there is a need to use wireless sensor networks for remote monitoring systems of power supply sources of telecommunication stations. Their use is economical and practically effective. One of the leading trends in wireless sensor technology is ZigBee based on the IEEE 802.15.4 [1], [2].

The IEEE 802.15.4 standard structure layers comply with the generally accepted OSI (Open System Interconnection) model standard. The main method of access to the physical environment used in this standard is random access with CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Additional features such as energy detection and link quality indication have also been implemented. For transmission, it can be used 16 channels in the 2450 MHz frequency, 10 channels in the 915 MHz frequency and 1 channel in the 868 MHz frequency [3], [4].

We have examined several studies by some researchers on modeling wireless sensor networks based on Markov chains [5], [6], [7], [8], [9], [10].

In this work, wireless sensor networks, in particular, the network based on the ZigBee standard were mathematically modeled based on various mathematical devices and their characteristics were studied. However, the development of a mathematical model of the operation process of the ZigBee standard wireless network for remote monitoring systems based on the Markov chain apparatus remains a topical issue. In this mathematical model, it is planned to take into account the load level of the network elements and the possible distortions in the transmitted packets as a result of interference.

Although it has been a long time since the ZigBee standard was developed, scientific interest in it has not diminished, as evidenced by the many scientific studies devoted to analytical modeling of wireless sensor networks and evaluating their performance under different conditions. Unfortunately, their features have not yet been fully taken into account when estimating the operation of sensor networks. Thus, the results obtained in the study were not used under conditions of "normal" load (unsaturated state of the network), when network station buffers are empty from time to time, and when transmitted packets are disrupted due to interference. In addition, changing the adjustable channel level parameters in IEEE 802.15.4 has different effects on its performance, which requires their optimization algorithms, and the instability of the protocol involves the development of conflict prevention mechanisms in the network. Thus, taking into account the load mode in the network (saturated and unsaturated states), the study of operating models of networks ZigBee, the interference effect, obtaining special algorithms to control channel level parameters based on them increases network bandwidth. Based on this, in this study we aimed to analyze the performance of the ZigBee wireless sensor network for monitoring systems at the MAC level, taking into account the load level at its stations and possible distortion of transmitted packets as a result of noise.

Main part

Sub-modeling of the operation process of the wireless sensor network based on ZigBee standard. In this paper, an analytical model of the ZigBee standard wireless network for remote monitoring systems is based on the Markov chain apparatus and network loads and possible distortions in transmitted packets as a result of interference are developed.Before developing the model, we divided the ZigBee standard wireless network operation process into three sub-models: batch service model, CSMA/CA model and virtual service time model. Figure 1 provides detailed information about the three sub-models and their interactions [11], [12], [13], [14].

In general, the embedded discrete-time Markov batch service model (abbreviated batch service model) as a virtual service time distribution ($p(T_b, t)$) and the Markov batch service model as a virtual service to determine the transition state matrix is used as the probability distribution ($p_s(T_b, t)$) of successful access to the channel from the time model [15], [16]. The Markov batch service model transition matrix helps to generate the probability distribution ($N_c(t)$) of the number of competing nodes. The number of competing nodes is used in the CSMA/CA to determine the steady-state probability of the CSMA/CA Markov chain. This helps to calculate the distribution of the return steps ($p_b(i, t)$). In the virtual service time model (VST model), the distribution of return steps ($p_b(i, t)$) is important both for the distribution of virtual service time and for the probability of successful access to the channel [17], [18].

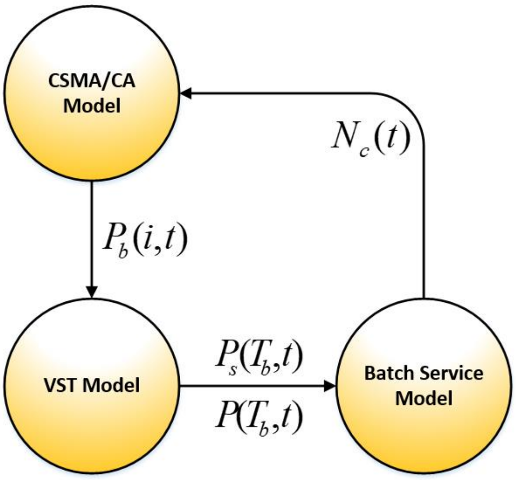


Figure 1. Submodels of the operation process of the wireless sensor network based on the ZigBee standard for monitoring systems.

Where $N_c(t)$ – the distribution of the number of competing nodes; $p(T_b,t)$ – the distribution of virtual service time; $p_s(T_b,t)$ – probability of successful entry into the channel; $p_b(i,t)$ – the distribution of the return phases [17].

Development of a markov chain that describes the assessment of the status of network stations based on the ZigBee standard. In this paper, we have taken as our main task the study of the CSMA/CA model based on the Markov chain. In developing the model, a wireless sensor network consisting of n elements of the monitoring system was studied. The M/M/1 model was used as a model of the ZigBee standard station (in terms of packet arrival and service process). According to him, the probability that the queue is empty for the k-element of the network can be determined as follows [19], [20], [21]:

$$\eta_k = 1 - \rho_k = 1 - \lambda_k / \mu_k , \qquad (1)$$

where ρ_k is the node load; λ_k and μ_k are the intensity of packet loading and intensity of packet processing, respectively ($k = 1 \ldots n$).

Assume that noise and interference may occur in the channel. Under their influence, the transmitted packet is disrupted, which in turn requires their repeated transmission. The probability of damage as a result of interference P_f of the L_p byte-length packet can be determined as follows [22], [23], [24]:

$$P_f = 1 - \exp\{-L_p \cdot BER\} , \qquad (2)$$

where BER (Bit Error Rate) is the probability of a bit error determining the intensity of the interference.

Hence, the probability of a network *k*-station failing to transmit a packet is determined as follows P_k [25].

$$P_k = 1 - (1 - P_f)(1 - P_c) = P_f + P_c - P_f P_c , \quad (3)$$

where P_c is the probability of collision (simultaneous transmission of two or more stations in the network).

The Markov chain (Figure 2) itself presents a two-dimensional random process, where b(t) and s(t) are the processes that lower the state of the countdown counter and its level, respectively [26], [27]. The state of the k-element of the network is written in the form $\{i, l\}$, here *i* is the delay stage with values in the range $(0, 1, \ldots, m + \Delta m)$, *m* is the maximum number of packet transmission attempts, Δm is the additional transmission stages; *l* is the time delay counter in the time interval $(0, 1, \ldots, W_i - 1)$, $W_i = 2^i W_0$ is the length of the "competition window" in the *i*-th stage of the delay. Status $\{-1,0\}$ indicates that the network element queue is empty. When a packet allowed for transmission appears, the network element with probability $(1 - \eta_k)/W_0$ will switch to one of the cases in the "0" row, where W_0 is the minimum length of the "competition window". If the attempt to transfer fails in the $\{i,0\}$ state, the network element with probability P_k / W_{i+1} will switch to one of the states in the $i+1$ row. If the packet is successfully transmitted, the network element with probability $(1 - P_k)\eta_k$ will switch to $\{-1,0\}$ (if the queue is empty) or if the buffer of this element of the network has a packet ready for the next transmission with probability $(1 - P_k)(1 - \eta_k)/W_0$ passes to one of the cases in the "0" row. When the network element reaches the *m* row, the competition time increases to the maximum value, while the network element tries to make repeated signals at the maximum, but fixed W_m size of the "competition window" no more than Δm.

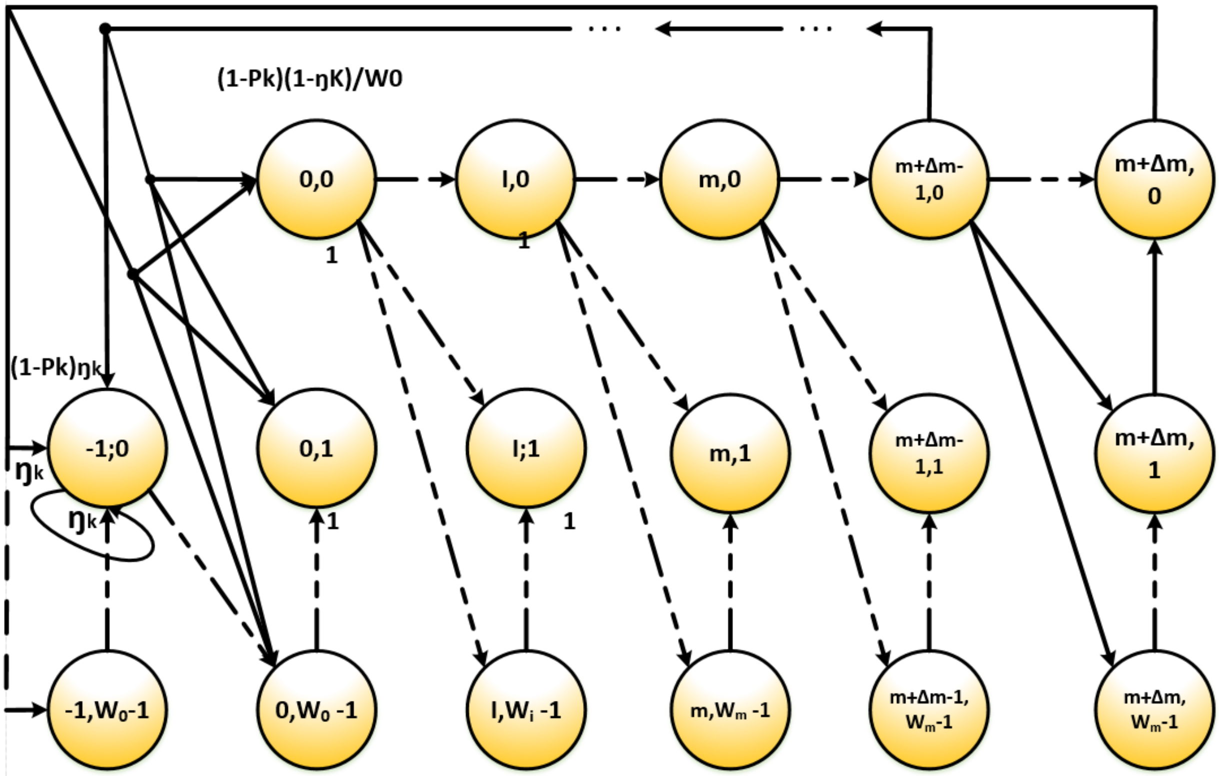


Figure 2. Markov chain describing the assessment of the status of network stations based on the ZigBee standard for monitoring systems.

When the network element reaches the $m+\Delta m$ stage and the delay counter is reduced to zero, the packet is either successfully transmitted with probability P_1, or dropped with probability P_2. In this case, the network element returns to the position $\{-1{,}0\}$ with probability η_k or returns to one of the states in the row "0" (if the queue has a ready packet for transmission). For the developed Markov chain, all possible one-step transitions between cases and their corresponding probabilities have been identified.

Creating analytical models by solving the markov chain. In this section, we describe the main characteristics of a WSN based on the ZigBee standard for a monitoring system and the analytical models obtained during their detection steps.

Through P_1 we determine the probability of data transmission in the time interval in which the network element is analyzed. It transmits the packet when the delay counter is reduced to 0. it is placed in the $\{i,0\}$ position. Therefore, the probability of transmission of the *k*-element of the network in the considered time interval is determined as follows:

$$P_{1_k} = \frac{2\left(1-P_k^{m+\Delta m+1}\right)}{\dfrac{2\eta_k\left(1-P_k\right)}{1-\eta_k} + \left(1-P_k^{m+\Delta m+1}\right) + W_0\left(\dfrac{\left(1-\left(2P_k\right)^{m+1}\right)\left(1-P_k\right)}{\left(1-2P_k\right)} + P_k\left(2P_k\right)^m\left(1-P_k^{\Delta m}\right)\right)} \quad (4)$$

Based on this expression, the probability of collision P_{col_k} is determined at the *k*-station of the network ($k=1\ldots n$):

$$P_{col_k} = 1-\prod_{i=1, i\neq k}^{n}\left(1-P_{1_i}\right) \quad (5)$$

The probability that at least one element of the network will make a transfer in this time interval is P_{tr}:

$$P_{tr} = 1-\prod_{i=1}^{n}\left(1-P_{1_i}\right) \quad (6)$$

According to this, the probability of a successful transfer P_s is determined as follows:

$$P_s = \frac{\sum_{i=1}^{n} P_{1_i}\prod_{i=1}^{n}\left(1-P_{1_i}\right)}{P_{tr}} \quad (7)$$

Then the lengths of all types of virtual slots for the basic input mechanism were determined:

$$T_s = T_c = T_{cca} + T_{pkt} + T_\sigma, \quad (8)$$

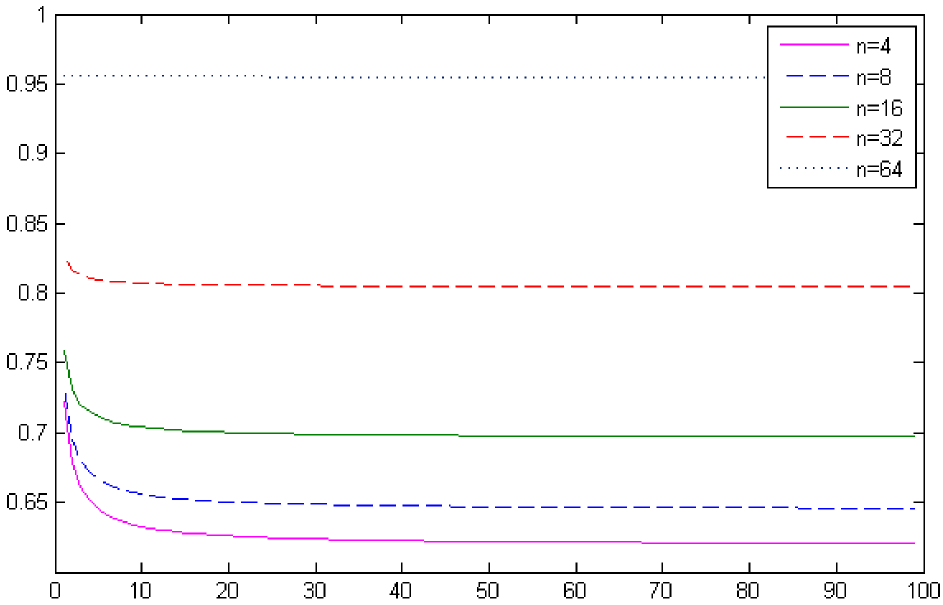
where T_s, T_c are the lengths of the "successful" and "collision" slots, respectively; T_{cca} is time intervals for CCA; T_{pkt} is average data packet transmission probability; T_σ is the length of the "empty" slot (no station transmits).

We have presented the normalized bandwidth of a channel in the form of the ratio of the average payload of information transmitted over a time interval to the average length of that time interval. Therefore, the expected bandwidth of the network in the saturated state is determined as follows [28]:

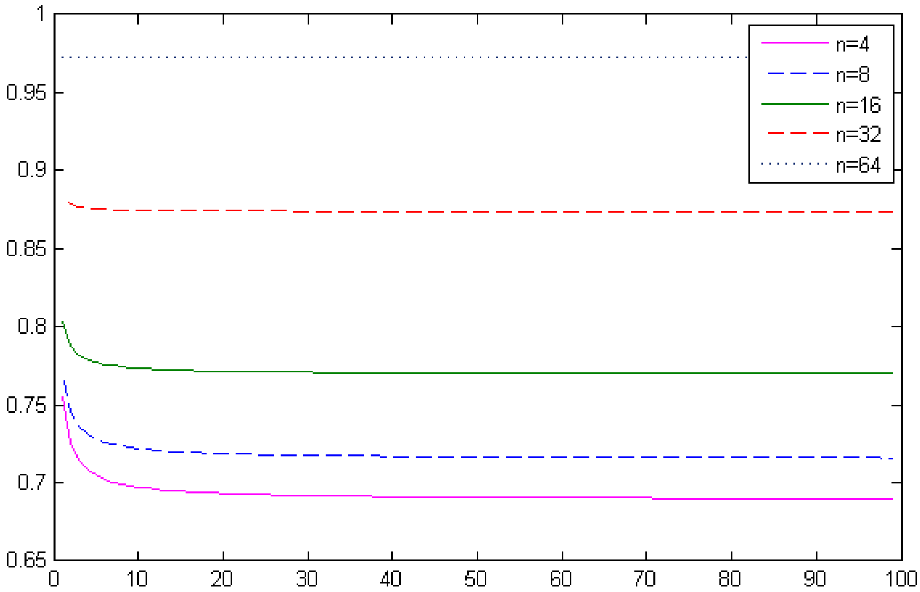
$$S_i = \frac{P_{tr} \cdot P_s \cdot L_p}{(1-P_{tr}) \cdot T_\sigma + P_{tr} \cdot P_s \cdot T_s + P_{tr}(1-P_s) \cdot T_c}. \quad (9)$$

In the next section, we evaluate the ZigBee standard wireless network characteristics for remote monitoring systems using the analytical expressions obtained.

Characteristics of the wireless sensor network depending on the system load. Figure 3 shows the graph of the dependence of the probability of successful transmission of packets on the system load when the maximum number of packet transmission stages is $m = 6$, the minimum length of the "competition window" is $W_0 = 8$. Figure 3.a evaluates the characteristics for the case where there is noise in the channel, that is, when the probability of packet failure is $P_f = 0.1$ and Figure 3.b for the absence of noise in the channel (ideal channel condition), that is, when the probability of packet failure is $P_f = 0$ for a different number of network nodes.



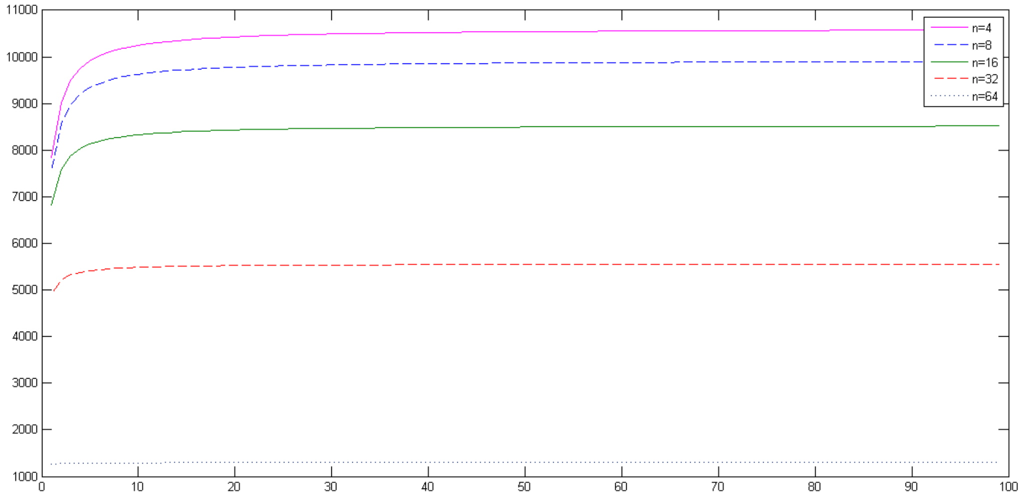
a)



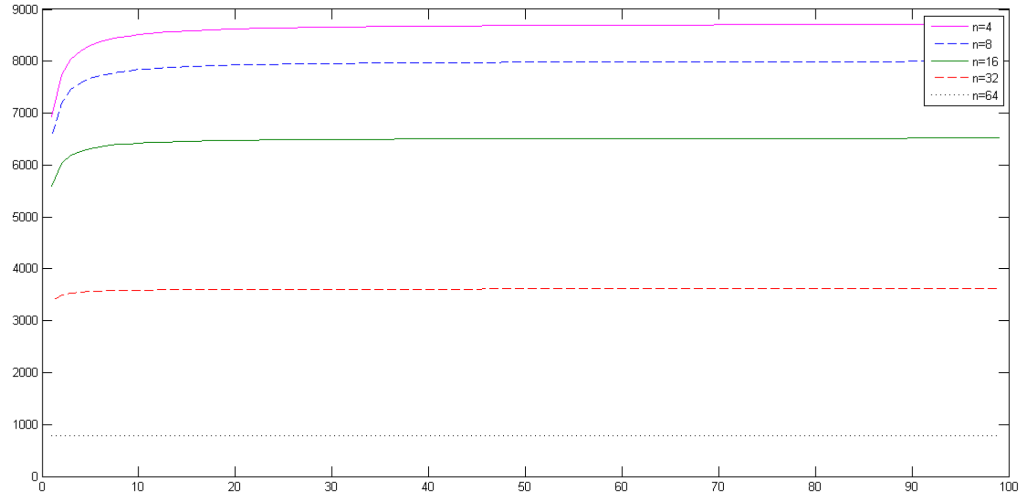
b)

Figure 3. Graph of the dependence of the probability of successful transmission of packets on the system load: a) $P_f = 0.1$; b) $P_f = 0$.

Figure 4 shows the graph of the dependence of network bandwidth on the system load when the maximum number of packet transmission stages is $m = 6$, and the minimum length of the "competition window" is $W_0 = 8$. Figure 4.a evaluates the characteristics for the case where there is noise in the channel, that is, when the probability of packet failure is $P_f = 0.1$ and Figure 4.b for the absence of noise in the channel (ideal channel condition), that is, when the probability of packet failure is $P_f = 0$ for a different number of network nodes.



a)



b)

Figure 4. Graph of the dependence of the bandwidth on system load: a) $P_f = 0.1$; b) $P_f = 0$.

Characteristics of a wireless sensor network depending on the number of nodes in the network. Figure 5 shows the graph of the dependence of the probability of successful transmission of packets on the number of nodes of the network when the maximum number of packet transmission stages is $m = 6$, and the minimum length of the "competition window" is $W_0 = 8$. Figure 5.a evaluates the characteristics for the case where there is noise in the channel, that is, when the probability of packet failure is $P_f = 0.1$ and Figure 5.b for the absence of noise in the channel (ideal channel condition), that is, when the probability of packet failure is $P_f = 0$ for different loading conditions in the network.

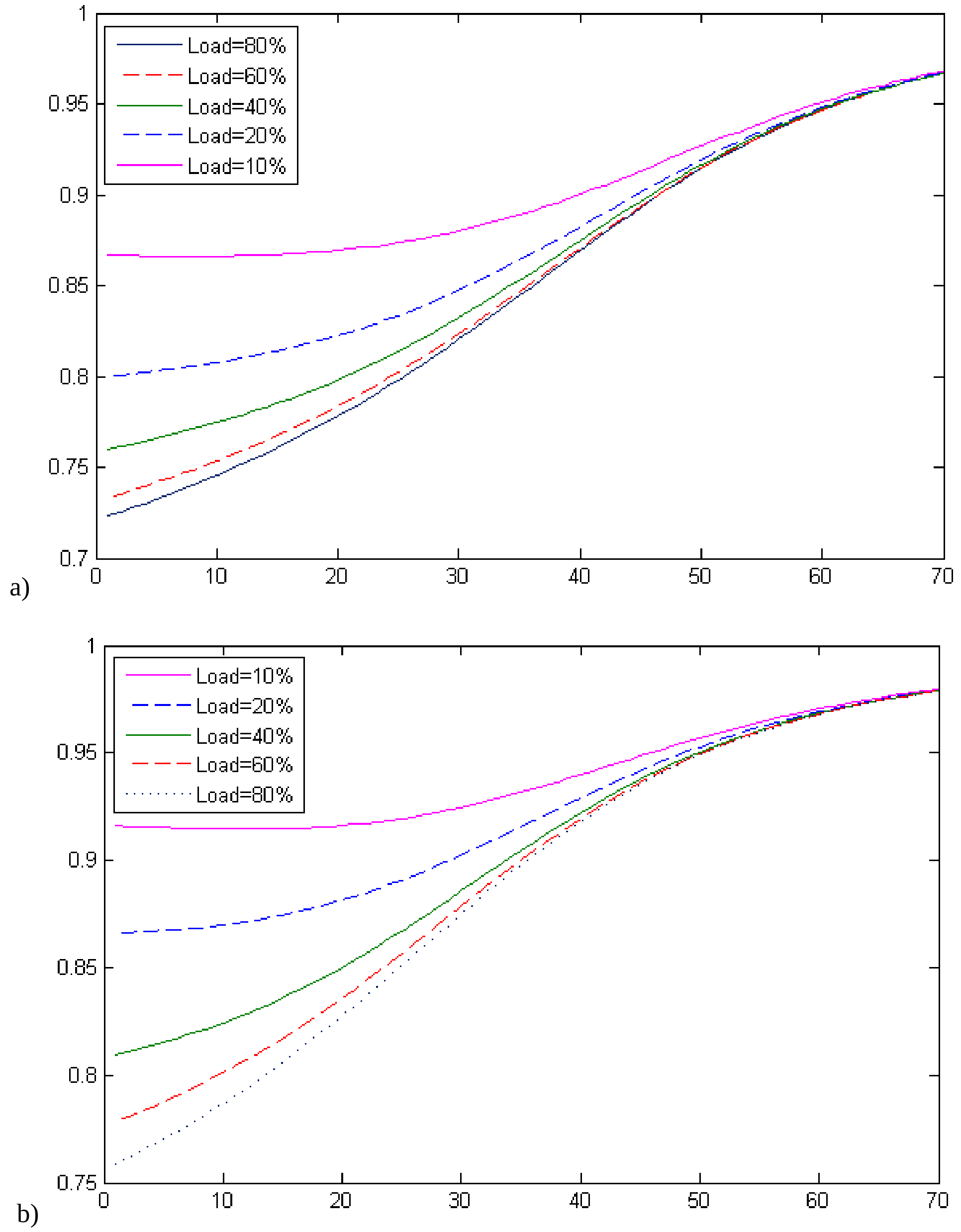
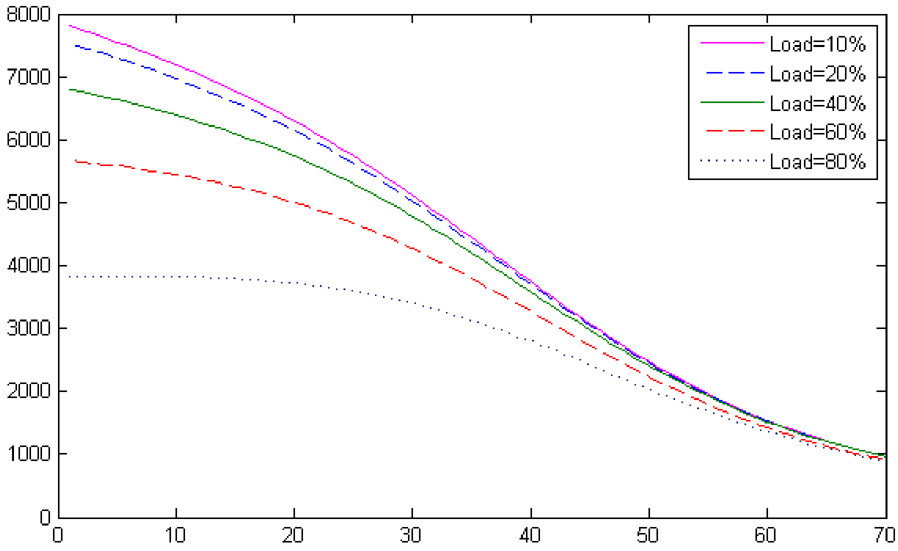
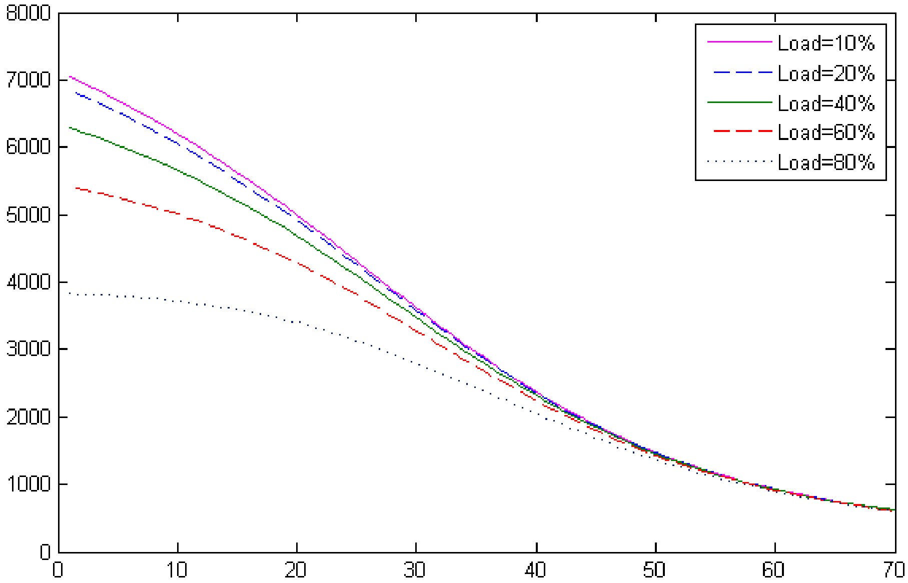


Figure 5. Graph of the dependence of the probability of successful transmission of packets on the number of nodes: a) $P_f = 0.1$; b) $P_f = 0$.

Figure 6 shows the graph of the dependence of network bandwidth on the number of nodes in the network when the maximum number of packet transmission stages is $m = 6$, and the minimum length of the “competition window” is $W_0 = 8$. Figure 6.a evaluates the characteristics for the case where there is noise in the channel, that is, when the probability of packet failure is $P_f = 0.1$ and Figure 6.b for the absence of noise in the channel (ideal channel condition), that is, when the probability of packet failure is $P_f = 0$ for different loading conditions in the network.



a)



b)

Figure 6. Graph of the dependence of the bandwidth on the number of nodes: a) $P_f = 0.1$; b) $P_f = 0$.

Conclusion

A mathematical model of operation process of the ZigBee standard wireless network for the monitoring system has been developed based on Markov chain apparatus and, unlike the known ones, takes into account the collision state of network stations and the distortion of transmitted packets as a result of noise. As a result of the modeling, analytical expressions were obtained to determine the bandwidth of the network, the probability of successful transmission of the packet and the refusal to service the packet. In terms of the obtained expressions, the characteristics were evaluated in the form of graphs. The algorithm we used was developed to adjust the channel-level parameters of the IEEE 802.15.4 wireless network, which provides an increase in network bandwidth by searching for the initial value of the "competition window" W_0 and the optimized (maximum bandwidth criterion) values for the number of packet retransmission m attempts. Using the developed algorithm, the efficiency of applying the W_0, m parameter adjustment mechanism was evaluated.

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