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Investigations of transmission delays in ZigBee networks

***Abstract**. The paper is devoted to the issue of determining and modeling of communication delays in Zigbee networks. The basis for the model is a description of the transmission between two arbitrarily selected nodes that transmit data between each other without other intermediate nodes. The model can be extended to describe complex transmission of the network, as shown in this publication.*

***Streszczenie.** Referat jest poświecony zagadnieniu wyznaczania i modelowania opóźnień komunikacyjnych w sieciach Zigbee. Podstawą do modelowania jest opis transmisji pomiędzy dwoma dowolnie wybranymi węzłami, które przesyłają pomiędzy sobą dane bez innych węzłów pośredniczących. Model można rozszerzyć tak, aby opisywać transmisję dla dowolnie złożonej sieci, co pokazano w niniejszej publikacji. (**Badania opóźnień transmisyjnych w sieciach ZigBee**).*

Keywords: delays, ZigBee, modeling, histogram.
Słowa kluczowe: opóźnienia, ZigBee, modelowanie, histogram.

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Introduction

In the measurement and control systems, data flow from the place of acquisition (transmitter) to the place in which they are used (receiver) is associated with the occurrence of delays [1]. In this paper assumed that the delay is a time between the moment of initiation of transmission in the transmitter and the time when the information is received by the receiver. The delay consists of packet processing delay in the node, time of access to the media and the message transmission time [2]. The media is seen as a signal of certain physical properties for the transmission of data by fixed environment called the transmission medium. If the measured parameter (i.e. temperature of an object) changes over time, these transmission delays can cause errors [3]. Errors caused by the delay, cumulating with other errors in the system, influences on accuracy data provided from transmitter to receiver. Therefore, there is a need to determine and described such a delays.

The delays in the wireless network can be due by various factors for example, the time of the processing tasks in the physical elements, the characteristics of the radio transmission channel, the influence of the environment on a radio signal, and with the microprocessor program in nodes [4]. Each of the devices used in the system requires adequate time to carry out their tasks. However, radio transmission channel is characterized by a large number of variable phenomena in space and time, which cause difficulties in the propagation of radio waves. The total delay consists of the structural delay, due to built wireless network (such as device configuration) and the additional delay [2]. The reason of additional delays lies in the existence of different factors that affect radio communications.

The advantage of wireless ZigBee networks is the possibility of repeating data, which didn't reach the receiver on the first attempt of transmission. Number of retransmissions can be determined by the user of wireless network if he has access to the configuration of radio equipment. Usually the number of retransmissions is equal to three.

Currently available delays models are very detailed, however, often do not take into account the possibility of retransmission of data and are difficult to describe and use.

In [2, 5] was described a model of communication latency using delta functions. The model was verify in simple cases. It was shown the effect of passive disorders such as walls and partitions for data latency and increasing the impact of distance on packet loss. In this publication does not describe how to verify the network model composed of more than two elements. This is a current problem because of nowadays development of any system to transmit data at small and large distances, eg for the transmission of meter readings, to monitor various physical quantities, etc.

ZigBee Protocol

ZigBee is the set of specs built around the IEEE 802.15.4 wireless protocol [6, 7]. ZigBee is designed to provide highly efficient connectivity between small packet devices. ZigBee devices are actively limited to a through-rate of 250 kbps, large pipeline of 1Mbps, operating on the 2.4 GHz ISM band, which is available throughout most of the world. In industry ZigBee is being used for next generation automated manufacturing, with small transmitters in every device on the floor, allowing for communication between devices to a central computer. This new level of communication permits finely-tuned remote monitoring and manipulation. Due to its low power output, ZigBee devices can sustain themselves on a small battery for many months, or even years, making them ideal for install-and-forget purposes, such as most small household systems.

The ZigBee network layer natively supports both star and tree typical networks, and generic mesh networks. Every network must have one coordinator device, tasked with its creation, the control of its parameters and basic maintenance. Within star networks, the coordinator must be the central node. Both trees and meshes allows the use of ZigBee routers to extend communication at the network level. ZigBee builds upon the physical layer and medium access control defined in IEEE standard 802.15.4 (2003 version) for low-rate WPANs. The specification goes on to complete the standard by adding four main components: network layer, application layer, ZigBee device objects (ZDOs) and manufacturer-defined application objects which allow for customization and favor total integration [6].

Delay model for ZigBee network

This chapter contains basic information related to the probabilistic model of transmission delays.

Considerations start from the simple case where two nodes communicate directly with each other using a wireless network, as shown in Figure 1 [5]. One of them (A) acts as a transmitter and the second one is a receiver of data. Between them there aren't other nodes which participate in the transmission.

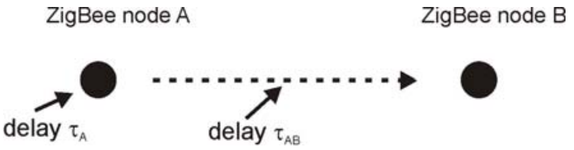

Fig. 1. Representation of communication delays in simplest case

Time delays shown in Figure 1 can be determined as:

- τ_A - The time witch takes a node A to gain access to the communication medium,
- τ_{AB} - The time required to send the message from node A to B.

In this case the transmission delay can be written as:

$$\tau_B = \tau_A + \tau_{AB} \quad (1)$$

For the probabilistic description of the components of expression (1) the probability density function was used. Probability density function of delay entered by node A (access to the transmission medium) can be described in general relationship:

$$g_{\tau_A}(\tau_A) = \begin{cases} g_A(\tau_A) & \text{for } \tau_{A1} \le \tau_A \le \tau_{A2}, \text{ where } \tau_{A1} \ge 0 \\ 0 & \text{for others} \end{cases} \quad (2)$$

The g_A is continuous and bounded function. When data are retransmitted probability density function $g_{AB}(\tau_{AB})$, witch describes the distribution of the delays caused by the transmission medium, can be described by a series [1]:

$$\begin{aligned} g_{AB}(\tau_{AB}) = a_0\delta(\tau_{AB} - \tau_0) + a_1\delta(\tau_{AB} - \tau_1) + \ldots + \\ + a_k\delta(\tau_{AB} - \tau_k), \end{aligned} \quad (3)$$

where: δ is the symbol of delta Dirac function [8], the number of moment is $i = 0,1, \ldots k$. Number of coefficients $a_0, a_1, \ldots, a_k$ in the series (3) is limited by a number of retransmissions. This coefficients have fixed and non-negative values. Assuming that the partial delay in the expression (1) are independent, the probability density function of the total delay is a function described as a convolution of functions of τ_A and τ_{AB} delays, which can be written as:

$$g_B(\tau_B) = g_A(\tau_A) \otimes g_{AB}(\tau_{AB}) \quad (4)$$

Expression (4) is actually the sum of components, each of which is the product of the coefficient and the delta function convolution for a given τ_k. Taking into account the relationship (1), it can be written as [2, 9]:

$$g_{Bi}(\tau_B) = g_A(\tau_A) \otimes \delta(\tau_B - \tau_i) = g_A(\tau_B - \tau_i) \quad (5)$$

After the transformation shown in [2] finally was obtained the relationship:

$$g_B(\tau_B) = a_0 g_A(\tau_B - \tau_0) + a_1 g_A(\tau_B - \tau_1) + \ldots + a_k g_A(\tau_B - \tau_k) \quad (6)$$

From equation (6) it follows that the probability density function of the total delay is the sum of the products, each of them is composed of two factors. One is the probability density function of the resulting delay in the node A when accessing the medium, shifted by the value of τ_i, the second one a_i is a weighting factor.

In each factor of the series (6) is the same probability density function g_A, shifted by τ_i and with the different scale coefficients a_i. It can be concluded that the function g_A is a kind of template mapped at different scales within the next factor of (6) [5].

Model presented in this form is suitable for the description of a simple network consisting of two nodes. Figure 2 shows an example of histogram obtained measuring delays between nodes where there is a sufficiently strong disorder that part of the data need to be sent repeatedly. Such tests are described in [2, 10, 11].

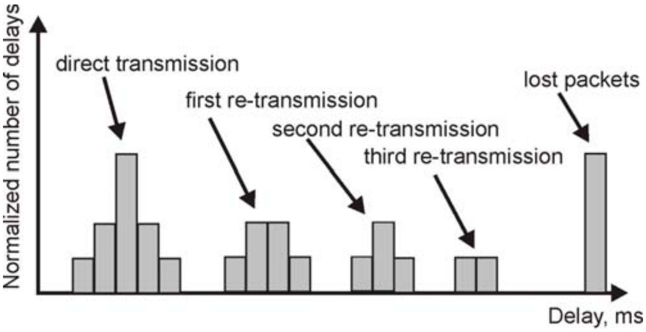

Fig. 2. Sample histogram of delays

Figure 2 shows and defines the modes of the resulting histogram. Transmission from node A to B is called the direct transmission while each new mod is another retransmission of data that have not previously been answered correctly. Some of the data that has not been sent in the last retransmission is illustrated as the last column on histogram described by the symbol of infinity. These packets are considered lost.

Delay model for complex cases

In most cases, wireless networks are built as large structures composed of many interconnected components according to the selected configuration such as star, mesh. The presence of nodes performing routing functions (extending range of a network, bypassing the damaged nodes) allows you to dynamically change the packet path in the event of damage to the existing route. The presence of the third element in the network can significantly affect the delay for this reason was designed measurement system consisting of three ZigBee modules (Fig. 3) connected in a star configuration. Transmitter and receiver were placed at a distance of 1 meter from each other in free space.

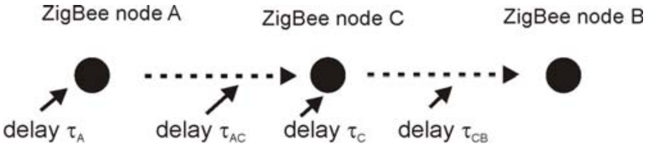

Fig. 3. Representation of communication delays in structure with three elements

Because of proper addressing the transmitter sends each incoming packet (e.g. from serial port input TxD) to the coordinator. Coordinator sends data to the receiver. Receiver decodes data and puts them on serial data output RxD. The measurement system measures the time between the start of transmission of data (application data input TxD), and their reception (the appearance of the output data RxD). Aggregated delay is given by the formula:

$$\tau_B = \tau_A + \tau_{AC} + \tau_C + \tau_{CB} \quad (7)$$

where: τ_A - delay associated with processing time and access to the media by the node A, τ_{AC} - time to send the message from node A to node C, τ_C - delay in the processing of data at the node C and obtaining access to the media by the node C to transmit data to node B,

τ_{CB} - time to send the message from node C to node B.

In the referred case in order to create a communication model all the components of the total delay have to be described by the probability density function as well as it was done before. And so:

- Probability density function of the delay τ_{A} can be described by the formula [2]:

$$g_{\tau A}(\tau_{\mathrm{C}}) = \begin{cases} g_{\mathrm{A}}(\tau_{\mathrm{A}}) & \text{for } \tau_{\mathrm{A1}} \le \tau_{\mathrm{A}} \le \tau_{\mathrm{A2}}, \text{ where } \tau_{\mathrm{A1}} \ge 0 \\ 0 & \text{for others} \end{cases} \tag{8}$$

- Probability density function of delay τ_{AC} is given by the series:

$$\begin{aligned} g_{\mathrm{AC}}(\tau_{\mathrm{AC}}) = {} & a_0\delta(\tau_{\mathrm{AC}} - \tau_{0k}) + a_1\delta(\tau_{\mathrm{AC}} - \tau_{1k}) + \ldots + \\ & + a_k\delta(\tau_{\mathrm{AC}} - \tau_{kk}), \end{aligned} \tag{9}$$

- Probability density function of the delay τ_{C} can be described as:

$$g_{\tau_{\mathrm{C}}}(\tau_{\mathrm{C}}) = \begin{cases} g_{\mathrm{C}}(\tau_{\mathrm{C}}) & \text{for } \tau_{\mathrm{C1}} \le \tau_{\mathrm{C}} \le \tau_{\mathrm{C2}}, \text{ where } \tau_{\mathrm{C1}} \ge 0 \\ 0 & \text{for others} \end{cases} \tag{10}$$

- Delay probability density function is given τ_{CB} series:

$$\begin{aligned} g_{\mathrm{CB}}(\tau_{\mathrm{CB}}) = {} & b_0\delta(\tau_{\mathrm{CB}} - \tau_{0n}) + b_1\delta(\tau_{\mathrm{CB}} - \tau_{1n}) + \ldots + \\ & + b_n\delta(\tau_{\mathrm{CB}} - \tau_{nn}). \end{aligned} \tag{11}$$

It should be noted that the time shift τ_{in} and τ_{ik} in the transmission delay model from node A to the coordinator and the coordinator node B is the same in both cases, and depends only from manufacturer of radio modules. This is associated with the retransmission time, and as indicated above is the same for a given repeat of packet. At the same time the number of repetitions is not always equal. This is due to the fact that the environmental conditions for each individual transmission may be different. For example, transmission of data from node A can interfere with some external factors and the number of repetitions will be k (that is, the maximum number retransmissions available for the modules), and transmission from node C to B can not be disturbed so there will be no retransmissions.

Based on the previous considerations can be said that for the equation (7) the probability density function g_{B} (τ_{B}) of transmission delay from node A to node B is expressed by the convolution of probability density functions describing the independent partial delay:

$$g_{\mathrm{B}}(\tau_{\mathrm{B}}) = g_{\mathrm{A}}(\tau_{\mathrm{A}}) \otimes g_{\mathrm{AC}}(\tau_{\mathrm{AC}}) \otimes g_{\mathrm{C}}(\tau_{\mathrm{C}}) \otimes g_{\mathrm{CB}}(\tau_{\mathrm{CB}}) \tag{12}$$

The properties of convolution is commutativity and associativity because of them each of the activities described by the formula (12) can be performed in any order. Substituting (8), (9), (10), (11) to (12) and performing the action, it can be shown that the total delay is given by the formula:

$$\begin{aligned} g_{\mathrm{B}}(\tau_{\mathrm{B}}) = {} & a_0 b_0 (g_{\mathrm{A}} \oplus g_{\mathrm{C}})(\tau_{\mathrm{B}} + \tau_{\mathrm{C}} - \tau_{0k} - \tau_{0n}) + \\ & + a_1 b_1 (g_{\mathrm{A}} \oplus g_{\mathrm{C}})(\tau_{\mathrm{B}} + \tau_{\mathrm{C}} - \tau_{1k} - \tau_{1n}) + \ldots + \\ & + a_k b_n (g_{\mathrm{A}} \oplus g_{\mathrm{C}})(\tau_{\mathrm{B}} + \tau_{\mathrm{C}} - \tau_{kk} - \tau_{nn}). \end{aligned} \tag{13}$$

Presented considerations show that the model is correct for more than two elements by using mathematical convolution operation. Total delay in the wireless network is a sub-sum of the delays introduced by the various elements of the transmission, as shown in Figure 4. The total delay in the message transmission from node A to node N is given by:

$$\tau_{total} = \tau_{\mathrm{A}} + \tau_{\mathrm{AB}} + \tau_{\mathrm{B}} + \tau_{\mathrm{BC}} + \cdots + \tau_X + \tau_{XN} \tag{14}$$

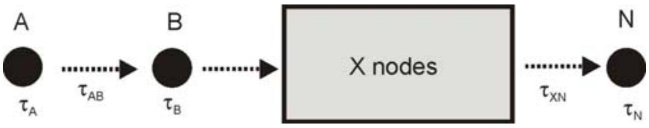

Fig. 4. Representation of communication delays in structure with multi elements

Since the described model is appropriate to describe the delay between any two nodes in the network, and can be extended to another node basing on the first model, it can be determined the distribution of the total delay $\tau_{\text{całkowite}}$. This allows to say that the developed model can also be used in networks where the components are modules of different manufacturers and for different disorders. Even when time delays introduced by the subsequent nodes are different (they can vary quite widely, even in the same measurement conditions, and the transmission of the same data) presented probabilistic model can be taken into account for each node.

As was shown it is possible to determine the model for a much more complex network configurations using successive convolution operations, but the path from the nodes A and B must be known. This occurs when nodes have fixed addresses of the node to which they transfer the data, the routing path is known. When the route of packet is not known it should be created a dedicated model for each subsequent data path (often in mesh networks).

The measuring system

As previously mentioned measurement system (Fig. 5) for registration delays is built of radio modules communicating in the ZigBee standard. One of the devices is connected to the microcontroller and its job is to send the data received from the microcontroller UART interface, via radio, to the next node [12]. To the microcontroller is connected receiver node. His job is to generate an interrupt request to the microcontroller after receiving data via radio. Microcontroller makes a comparison of data and measures time between the send and receive of data. This time it is sent to the PC as a communication delay, but only when the data sent is the same as the data received [10,13].

Between the transmitter and the receiver in the system shown in Figure 5 can occur any number of the ZigBee nodes, however, studies were conducted for the three components as shown in Figure 3 in order to confirm the applicability of the model.

Making measurements described delays in the case (for 3 or more nodes) is not without some difficulties. Namely, after receiving the final results, it is unclear which part of the measurement channel abnormalities and consequently retransmissions of data. The resulting histogram delays may also be difficult to interpret due to overlapping fashion from several histogram of direct transmission and retransmission of data. For this reason, it was important to measure in a simple case and determination of the components of delay so that in the future you could set the delay to more complex networks. It is also important registration data (delay) of the intermediate device between the extreme transmitter and receiver.

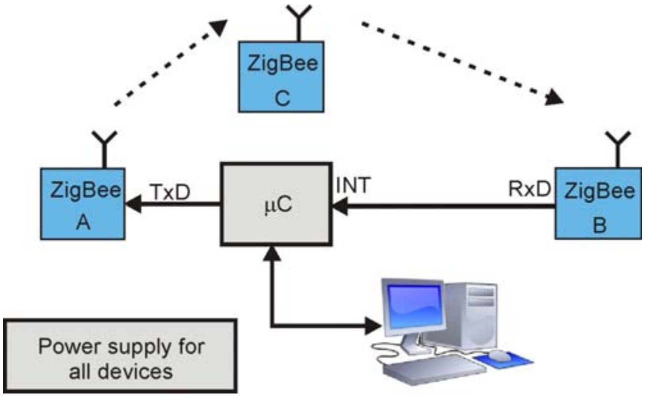

Fig. 5. Measurement setup

The study used wireless modules from Digi International - XBee PRO S2. The modules described in [10]. Their advantage is easy implementation in various measurement systems especially from the programming site. Average delay measured in the system consisting of two such a devices is about 8 ms for transmission of individual bytes of data. Obtained histograms are quite easy to interpret because of the separation of the modes of the histogram at the time scale witch was visualized in Figure 2. The modules have a small range (about 100 m), which allows to perform measurements on relatively small areas.

How to compare the results

Part of the research work was carried out in a simulation way before real measurements. From the partial models measured for various disorders and radio modules, using a convolution set a total delay model for whole network. This model was then compared with the actual measured model.

As a result of each measurement (real or simulated) is a histogram usually multimodal. So there is a need to compare the different histograms to determine their degree of similarity. Such a coefficient will allow to distinguish which parameters of histogram have changed (eg, number of retransmissions, the number of retransmitted data). In this paper was decided to use a simple method based on the comparison of histograms areas. It is clear that compared histograms are composed of the same number of modes.

The coefficient for the comparing histograms *r* is taken as the square root of the difference between the areas of compared histograms, according to the formula:

$$r = \sqrt{\sum_{i=1}^{n} \left(P_{1,i} - P_{2,i}\right)^2} \tag{15}$$

where: i - the mod number, n - number of modes, $P_{1,i}$ - the surface area of the i-th mod of the first histogram divided by the median of the distribution of this mod, $P_{2,i}$ - the surface area of the i-th mod of the second histogram divided by the median of the distribution of this mod.

The use of any coefficient needs to define the boundaries when you can declare the two histograms to be similar and when they do not. Selection of the border is a matter of convention and depends largely on the purpose use of the wireless network. In time-critical applications, the discrepancy between the actual and model histogram can't be large, but where delays aren't and packets are transmitted with high redundancy, then the difference may be greater.

The test results and simulation

The study began with a real measuring for obtain partial models in the system shown in Figure 6.

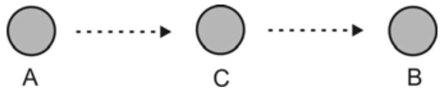

Fig. 6. Placement of wireless modules for determining the total delay model

First was determined delay model between components A and C and between C and B. It was assumed that between these parts there are no obstacles such as walls and other architectural features. The study was conducted in the absence of other wireless networks (Zigbee, WiFi) operating in the measurement area.

In Figure 7 is presented actual delay histogram between two nodes A and C. The average value of the delay is 8.1 ms.

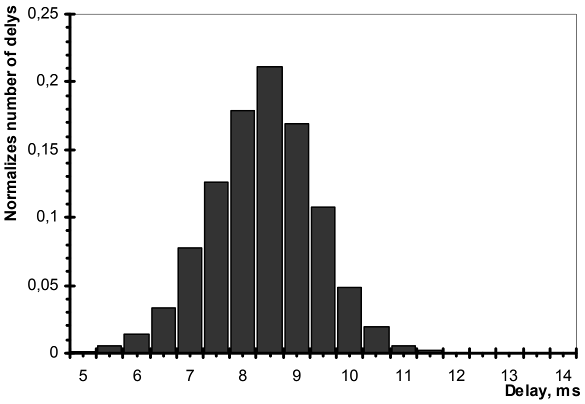

Fig. 7. Histogram of delay between nodes A and C

Delay measurement was also made between the nodes C and B and recorded histogram is show in Figure 8. Its average value is the same as in the previous case, since the measurement parameters are the same (transmit one byte 55H, at the same speed, in the absence of external disturbances, for the same wireless modules).

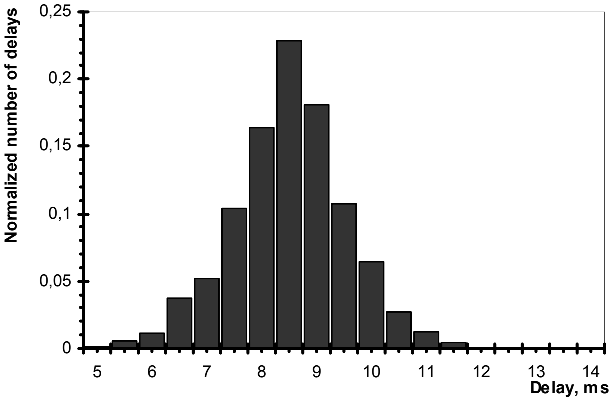

Fig. 8. Histogram of delay between nodes C and B

For fhe histograms in figures 7 and 8 the model equation can be written as follows:

$$g_{\mathrm{B}}(\tau_{\mathrm{B}}) = 1 \cdot g_{\mathrm{A}}(\tau_{\mathrm{B}} - 8{,}1) \tag{16}$$

As can be seen the two histograms are very similar and are described by the same equation. One before function expression shows that 100% of packets sent from the transmitter reaches the receiver during the transmission. Average value of the delay is also the same. Hence the necessity of determining the difference between the histograms as the factor in this case it is 0.06. This means that there are some differences in the shape of histograms obtained.

From partial histograms were determined total latency histogram using the convolution operation. Simulations were performed in Matlab and OPNET Modeler, which is dedicated to the simulation of computer networks [14, 15]. The resulting histogram is shown in Figure 9

It may be noted that the average delay is two times higher than for the partial cases. Delay model can be written as:

$$g_B(\tau_B) = 1 \cdot g_A(\tau_B - 16{,}2) \tag{17}$$

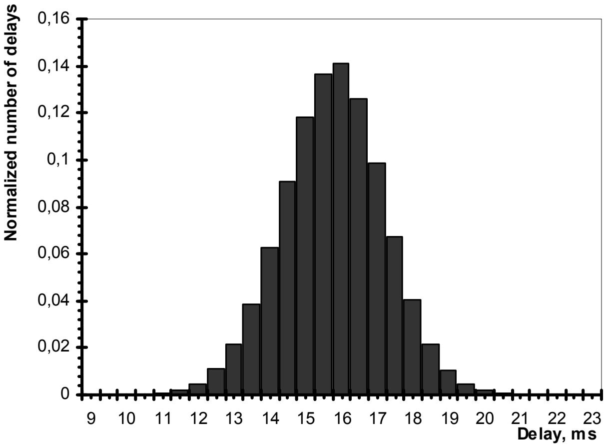

Fig. 9. Simulated histogram of delay between nodes A and B

Then, the measurement system was built according to the presented scheme and the delay measurements was made. The obtained histogram is shown in Figure 10. The average value recorded for the delay is slightly less than that obtained in a simulation. The distribution of the total delay in this case, is given by:

$$g_B(\tau_B) = 1 \cdot g_A(\tau_B - 15{,}5) \tag{18}$$

Another value of the average delay may be related to a simplified model of an intermediate node in the transmission. This node in contrast to the first node (A) does not need to form a data packet or to wait for more data, which can reach in time (for example, serial port), it sends a data packet unchanged to the node B, thus less time processing.

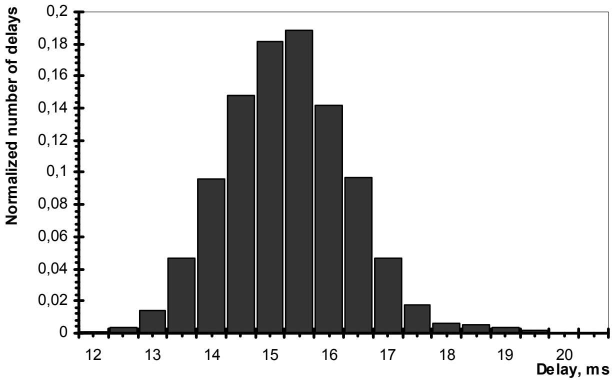

Fig. 10. Measured histogram of delay between nodes A and B

Using the criterion of comparing histograms obtained r value is equal to 0.17. This means that described coefficient is much more sensitive to changes in time than the shape of the histogram.

Fig. 11. Placement of wireless modules for determining the total delay model with four nodes

Another measure was to introduce the fourth network node to the test, as shown in figure 11. That node in the figure is placed between the nodes C and B, as node D. The measured latency of the node is shown in figure 12.

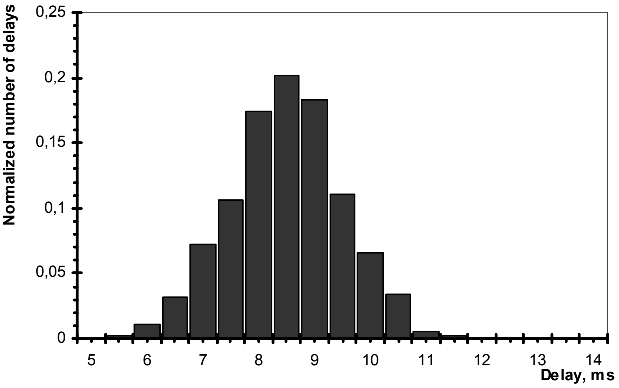

Fig.12. Histogram of delay between nodes C and D

In this case it can written:

$$g_D(\tau_D) = 1 \cdot g_C(\tau_C - 8{,}1) \tag{19}$$

which means that the median of the histogram obtained is the same as for the previous cases. That confirms that the measured delay between any two nodes is always the same, assuming the same conditions of measurement. The total delay in the system shown in figure 11 will be dependent on the delays of all sub-nodes. In this case, the model of the delay is given by:

$$\begin{aligned} g_B(\tau_B) = {} & a_0 b_0 c_0 (g_A \otimes g_C \otimes g_D) \\ & (\tau_B + \tau_C + \tau_D - \tau_{0k} - \tau_{0n} - \tau_{0m}) + \\ & + a_1 b_1 c_1 (g_A \otimes g_C \otimes g_D) \\ & (\tau_B + \tau_C + \tau_D - \tau_{1k} - \tau_{1n} - \tau_{1m}) + \ldots + \\ & + a_k b_n c_m (g_A \otimes g_C \otimes g_D) \\ & (\tau_B + \tau_C + \tau_D - \tau_{kk} - \tau_{nn} - \tau_{mm}). \end{aligned} \tag{20}$$

This is the convolution of the three functions describing the delay introduced into the measuring circuit by a further network nodes. Designated simulation delay histogram is shown in figure 13.

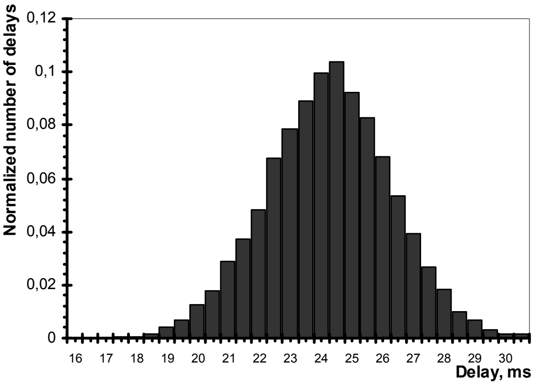

Fig.13. Simulated histogram of delay between nodes A and B

The resulting histogram allows to say that the model of delay has a form:

$$g_B(\tau_B) = 1\cdot(g_A \otimes g_C \otimes g_D)(\tau_B + \tau_C + \tau_D - 24{,}3) \tag{21}$$

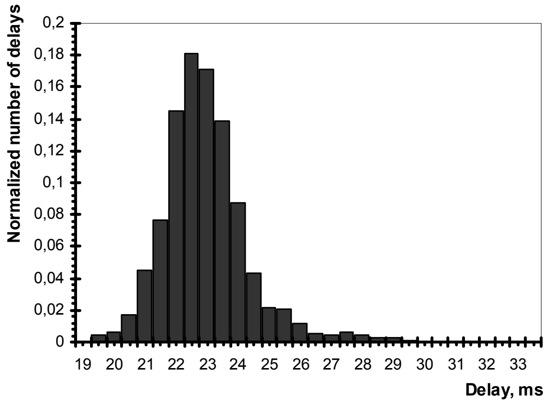

Fig.14. Measured histogram of delay between nodes A and B

After testing of the delay for designed network by measuring system was obtained histogram shown in figure 14, which can be described by the model:

$$g_B(\tau_B) = 1\cdot(g_A \otimes g_C \otimes g_D)(\tau_B + \tau_C + \tau_D - 22{,}8) \tag{22}$$

It may be noted that the average packet delivery time is shorter in reality then from the simulation. This confirms that the intermediate nodes in the transmission delay bring a lot smaller delay than the node which starts transmission. However, this requires further testing.

Coefficient *r* in this case is 0.33. Its value increased as the histograms of the figures 13 and 14 are displaced in time by a large value.

Conclusion

The studies showed that the problems with modeling delays in ZigBee networks consisting of more than two elements. The work shows the model to the description of the delays in the increasingly complex cases. Real and simulation studies used to detect a variety of time dependencies and identify their source. The study shows that the node that sends data only (acting as a router) introduces less delay than the transmitter node. The study also suggested as comparing histograms based on surface area of the resulting graph. This measure can determine whether the two histograms are similar. Increasing the value of the coefficient means that histograms are themselves less similar. The research shows that the given ratio is much more sensitive to changes in latency than the change in shape histograms obtained.

Further work will focus on identifying the causes of the delays introduced by various suitable and routing node, as well as ways to improve the comparison of multimodal histograms.

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