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Analysis of the time slot length impact of selected data link layer protocols on energy resource consumption in wireless sensor networks

Paweł Dymora[1*], Mirosław Mazurek[1], Kamil Łyczko[1], Zdenek Hadas[2]

[1] Faculty of Electrical and Computer Engineering, Rzeszów University of Technology, 35-959 Rzeszów, al. Powstańców Warszawy 12, Poland
[2] Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2, 61669 Brno, Czech Republic
* Corresponding author's e-mail: pawel.dymora@prz.edu.pl

ABSTRACT

The paper analyzes the effect of time slots on the correctness of packet delivery for selected media access control (MAC) protocols of wireless sensor networks (WSN) like B-MAC (Berkeley MAC), L-MAC (lightweight medium access protocol), and X-MAC protocol (enhanced MAC protocol compared to B-MAC). In the study, reliability, and power consumption were used as indicators of the quality of the protocol variant. The length of the time slot was shown to affect the consumption of energy resources of the nodes. For all network sizes considered, it was shown that the best results were achieved by the L-MAC protocol, which also proved to be the most energy-efficient with a low ratio of energy resource consumption. The X-MAC protocol has significant advantages and can be easily implemented on nodes running packet-switched wireless transceivers.

Keywords: sensors; energy-efficient; WSN; B-MAC; X-MAC; LMAC; OMNeT++.

INTRODUCTION

Wireless sensor networks are widely used in various areas of the current world. They have contributed significantly to the development of industry and are an integral part of solutions related to Industry 4.0. They can be considered the basis of the Internet of Things (IoT). They enable the collection of various types of data describing the surrounding sensor environment and can be used in many applications [1–3].

The communication process of sensor networks may be controlled by various common and specialized protocols. They are specially designed to be able to ensure the lowest possible consumption of memory and energy resources of nodes while maintaining an appropriate level of transmission quality. Sensor networks, therefore, differ from classical computer networks. In [4] the protocol stack used in wireless sensor networks was presented. It consists of 5 layers: physical, data link, network, transport, and application. The protocols of each tier perform rest functionalities and work closely with the protocols of neighboring layers to ensure optimal network performance. Many algorithms differ in their implementation and the way they perform their tasks. Network traffic analysis is an important process to study their performance and learn about their impact on the nature of network operation. There are also many complex solutions on the market today that support multiple layers of the stack. Selected examples of protocols mentioned in industry articles [5–10] are ZigBee, Wi-Fi, 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks, Thread, or Z-Wave.

The media access control (MAC) protocol is a Layer 2 protocol in the OSI model, whose task is to manage access to the transmission medium, particularly in networks with multiple devices sharing the medium, e.g. Ethernet or wireless networks. It enables the coordination of data transmission to avoid collisions and ensure smooth communication. Generally, MAC protocols for WSNs can be divided into three main types: allocation-based MAC protocols (Frequency-Division Multiple Access (FDMA)/Time-Division Multiple Access (TDMA)/Carrier Sense Multiple Access (CDMA)), competitive MAC protocol, and hybrid MAC protocol. Instead of periodically transmitting data, sensor nodes in the network will transmit data only when an emergency occurs (e.g., monitoring value exceeds a threshold) or receive query instructions. Therefore, it is appropriate to use a competitive MAC protocol. There are several common types of competitive MAC protocols in WSNs: S-MAC (Sensor-MAC) protocol, T-MAC (Timeout-MAC) protocol, B-MAC (Berkeley MAC) protocol, and X-MAC protocol, which is an improved protocol compared to B-MAC [20].

The use of MAC protocols was always associated with high power consumption and packet loss [11]. Sensor nodes consume more power when they need to transmit data, and power consumption depends on many factors. One of them is mobility and distance [12]. In the process of designing protocols for wireless sensor networks, various factors should be taken into account due to the nature of this type of network. The solutions being prepared must manage the energy resources of the nodes appropriately. The devices building the network are mostly battery-powered and in order to achieve the longest possible operating time, algorithms should implement energy-saving mechanisms [13, 14]. The protocols must not be too complicated and generate too much traffic, this is also due to the limited computational capabilities of the nodes. Algorithms should also support scalability, as sensor networks can include very many nodes. The transmission delays achieved must meet certain requirements so that messages in the network are transmitted in a timely manner. This is a critical requirement for some applications. It is also desirable for protocols to be resilient to the dynamic nature of the network and support changes that occur in the topology due to damage or shuffling of nodes [15, 16]. B-MAC (Berkeley MAC) is a MAC protocol that has been widely used in Wireless Sensor Networks (WSN). It has been designed specifically for sensor networks with low energy consumption. The B-MAC uses a 'wake-up control' (listening preamble) technique that allows sensors to save energy by going into a low activity state and periodically checking if the medium is busy [11–13]. On the other hand, one can find the L-MAC (Lightweight MAC) protocol, which is a simplified version of the MAC protocol designed to minimize energy consumption and simplify implementation in devices with limited resources (e.g. sensor nodes). Its structure is lightweight and its efficiency ensures high responsiveness to dynamic network conditions [4, 13–15]. Another interesting version is the X-MAC protocol (which is an improved version of the protocol over B-MAC), designed to save even more energy and reduce latency. X-MAC uses shorter listening signals (strobes) to capture transmissions faster and adjust the response of sensor nodes, reducing wake-up time [15–17].

These protocols are mainly used in the context of Wireless Sensor Networks (WSNs), where efficient power management is key. Each of these protocols represents an evolution and attempt to optimize access to the medium to suit the needs of the network. WSN connects sensors to computer networks and enables very dense on-site and live data measurements over a large area. Because this technology can be embedded almost anywhere in countless applications, interference between different networks can become a serious problem. For most WSNs, it is now assumed that access to the network medium is non-competitive, and it is important to ensure transmission reliability [17].

The autonomous character of sensors in WSNs and their ability to operate without the support of a predefined infrastructure makes them effective in collecting data in a variety of areas, even in harsh environments. However, power consumption remains one of the main design challenges, due to the limited energy resources provided by the batteries in the sensor node. In this paper, analytical contributions and a simulation model are presented for the feasibility of efficient estimation of energy consumption and transmission delay for the investigated MAC protocols. In particular, it is shown that X-MAC can be used in low-power WSNs with short, constant arrival times between packets.

SELECTED CHARACTERISTICS OF MAC AND NETWORK LAYER ALGORITHMS

In [4], the authors prepared, based on a literature review, a summary of performance evaluations of MAC layer and network layer protocols in terms of node energy resource consumption, network lifetime, scalability, and over-provisioning, among others. For the first category, a comparison of the performance of the following protocols is presented: S-MAC (Sensor-MAC), T-MAC (Timeout-MAC), B-MAC (Berkeley MAC), PW-MAC (Predictive Wake-up MAC), and PEDAMAC (Power Efficient and Delay Aware MAC). Table 1 summarizes the selected characteristics of the mentioned algorithms:

For example, the high throughput of the B-MAC protocol is due to its preamble sampling mechanism, which involves sending a message before data transmission informing the addressee of the incoming packet and thus allows to reduce the duty (activity) cycle. PW-MAC, on the other hand, allows for a relatively high level of energy savings and low latency thanks to a mechanism for predicting the timing of activation of the receiving node by the node sending the message in order to achieve synchronized timing of activation of both devices. In the case of the PEDAMAC protocol, a relatively high overhead associated with the transmission of control messages is present, and low scalability is the result of using low transmission powers. Concerning the energy consumption of a single node, the S-MAC protocol has the worst statistics, while the T-MAC protocol proved to be the most energy-efficient. It saved 85% more resources than S-MAC.

For network layer protocols, a comparison of the performance of the following algorithms was presented: "Flooding and Gossiping", SPIN (Sensor Protocols for Information via Negotiation), "Directed Diffusion", LEACH (Low-Energy Adaptive Cluster Hierarchy), LEACH-SM (LEACH with Spare Management), DEEC (Distributed Energy Efficient Clustering) and BLR (Beacon-Less Routing). LEACH-SM is a modification of the LEACH protocol that introduces support for additional nodes that are normally dormant and are activated when energy resources in the network are depleted. DEEC is a hierarchical protocol that supports dynamic changes of cluster heads depending on the current energy resources of nodes in order to extend the life of the network. BLR, on the other hand, is a node location-based protocol and uses a mechanism called dynamic forwarding delay to select the next hop node for a transmitted message, which helps reduce protocol overhead. Table 2 summarizes the performance of the presented protocols in terms of energy consumption, network lifetime, and scalability.

Based on the table presented it can be concluded that the SPIN protocol is characterized by relatively low energy consumption of nodes. This is due to the fact that the algorithm employs a metadata mechanism that makes it possible to reduce the size of transmitted packets and thus limit the amount of data distributed in the network. This significantly reduces the computational overhead imposed on nodes and consequently reduces the consumption of their energy resources. The BLR protocol, on the other hand, is characterized by high scalability due to the relatively low level of protocol overhead made possible by not using Hello broadcast messages. Networks based on LEACH-SM and DEEC protocols, on the other hand, have the longest lifetime.

RESULTS AND DISCUSSION

In the study of wireless sensor networks, IT tools are very helpful. Traffic simulators allow the creation of a model of the network and generate data carrying information about its characteristics without the need to build a physical architecture. This data can be the basis for various types of analysis, which are possible to carry out in various software environments. The research used the OMNeT++ simulator (Operation and Maintenance New Equipment Training) [18] and the RStudio environment [19]. The library used was INET, which provides a set of ready-made models related to communication networks. It contains modules implementing, for example, different protocols, types of devices, radio communication medium, or types of applications that generate the corresponding network traffic. The

Table 1. Performance comparison of selected versions of MAC protocols [4]

Protocol	Throughput	Energy conservation	Latency	Scalability
S-MAC	Low	Low	High	High
T-MAC	Low	High	N/A	Low
B-MAC	High	Moderate	Moderate	Low
PEDA-MAC	Moderate	Moderate	Low	Low

Table 2. Performance comparison of selected routing protocols [4]

Protocol	Energy consumption	Network lifetime	Scalability
Flooding and gossiping	High	Small	Low
SPIN	Low	Small	Low
Directed diffusion	Moderate	Small	Low
LEACH	High	Medium	Moderate
LEACH-SM	Moderate	Long	Moderate
DEEC	Low	Long	High
BLR	Low	Moderate	High

work uses, for example, the SensorNode module, which by default models the operation of a wireless network node with an interface based on the IEEE 802.15.4 standard. The parameters of the modules are modifiable, so it is possible, for example, to change the type of radio used or the protocols used. The B-MAC, X-MAC, and L-MAC data link layer protocols are implemented by BMac, XMac, and LMac modules, respectively.

The publication includes a study of the impact of changes in the value of the parameter that determines the time slot length for data link layer protocols: B-MAC, X-MAC, and LMAC, and a comparison of the consumption of energy resources by nodes in sensor networks based on these protocols. The simulated networks were built in a star topology. At the center of the architecture was a node acting as the main gateway. The number of sensors in the network and the distances between the main gateway and the sensors, as well as the server, were paired and set accordingly depending on the simulation being carried out. 50% of the number of all sensors were type 1 sensors, 30% were type 2 sensors, and the remaining sensors were type 3.

The module called SimMAC describes the components that make up the structure of the entire network. Variables modifying its form have been defined in the parameters section. The first 4 of them are used to determine its size - the number of all sensors in the network and the number of sensors of each type. The next 7 variables are used to describe the distance between individual nodes and to modify their location. The distFromSensorToSink and distFromServerToSink variables express the distance between a single node and the gateway, and between the server and the gateway, respectively. gatewayX, gatewayY, serverX, and serverY store the location coordinates of the gateway and server. The angleStep variable is used in sensor position calculations and expresses the angular distance in radians between adjacent sensors on a circle centered on the gate. The last variable in the list of network parameters is a flag informing whether visualizations should be active during the simulation (when running it in graphical mode). With the help of the @display property, the dimensions of the simulation area (500 by 400 m) were additionally defined. The submodules section defines the components of the simulated network module. In the beginning, the lists sensorType1, sensorType2, and sensorType3 were declared for storing sensor objects of the appropriate types. The proprietary StartSensorNode module, which is a modification of the SensorNode component, was used here, enabling the appropriate placement of the node in the star topology network.

The gateway and server components, on the other hand, implement the main gateway and the server, respectively. In the first case, the SensorNode module was used and the radio range display option was configured using the enableVisualisation parameter of the parent SimMAC component. The StandardHost module was used for the server. The next 3 components are defined respectively: device network settings configurator (Ipv4NetworkConfigurator), network events visualization module (IntegratedVisualiser), and radio medium simulating module (ApskScalarRadioMedium). In the simulations, a simple implementation of the ApskScalarRadio radio module was used, which by default uses BPSK (Binary Phase Shift Keying) modulation. Radio parameters were selected on the basis of The last section in the network definition defines a permanent 100 Mb/s Ethernet connection between the wired interfaces of the gateway and the server.

The functionality of the sensors was modeled by UdpBasicApp modules. Type 1 devices emitted 25B data packets regularly every 1s. Type 2 sensors sent 10 bytes of data with intervals ranging from 0.2 to 0.5 s (a random value calculated using the uniform() function). Type 3 sensors, on the other hand, sent 40B packets at 5s intervals. The devices started communication at a random moment in the first second of the simulation (the value returned by the exponential() function). The recipient of the packets was the server executing the UdpSink application.

In the case of MAC protocols research, the effect of time slot length changes on the correctness of packet delivery was analyzed. The B-MAC and X-MAC protocols are based on the CSMA mechanism, and the length of the time slot in their case means the time spent in sleep mode between wake-ups and checking the occupancy of the medium. For the L-MAC protocol, which uses the TDMA technique, on the other hand, this parameter means the duration of a single transmission window for a node. For each of the aforementioned protocols, network sizes ranging from 5 to 50 sensors were simulated (with a step of 5). For each network size, tests taking into account different time slot lengths were run:

- B-MAC and X-MAC protocols: a time slot length ranging from 0.01 s to 0.3 s (with a step of 0.01 s),
- L-MAC: from 0.05 s to 0.3 s (with a step of 0.01 s).

Each test simulated network operation throughout the 100s. The number of packets sent by each sensor, the number of packets received by the server, and the energy consumption of the sensors and the main gateway were recorded. For each test, the correctness of packet delivery (the quotient of the number of packets received and the sum of the number of packets sent) and total energy consumption were calculated. The obtained results were averaged for each of the tested parameter values, and finally, for each protocol, the length of the time slot that allowed to achieve the best network reliability (the highest percentage of correctly delivered packets) was indicated. Subsequently, simulations of the operation of networks with sizes ranging from 5 to 20 sensors based on MAC protocols were carried out with the time slot length indicated earlier as the best, and the aggregate consumption of energy resources by wireless nodes was compared. A visualization of an example from the simulated networks is shown in Figure 1.

The average values of the packet delivery correctness statistics were the basis for selecting the best value of the time slot length parameter for each of the protocols tested: B-MAC, X-MAC, and L-MAC. The decision was made based on a graph of the dependence of the average correctness on the value of the parameter (Fig. 2).

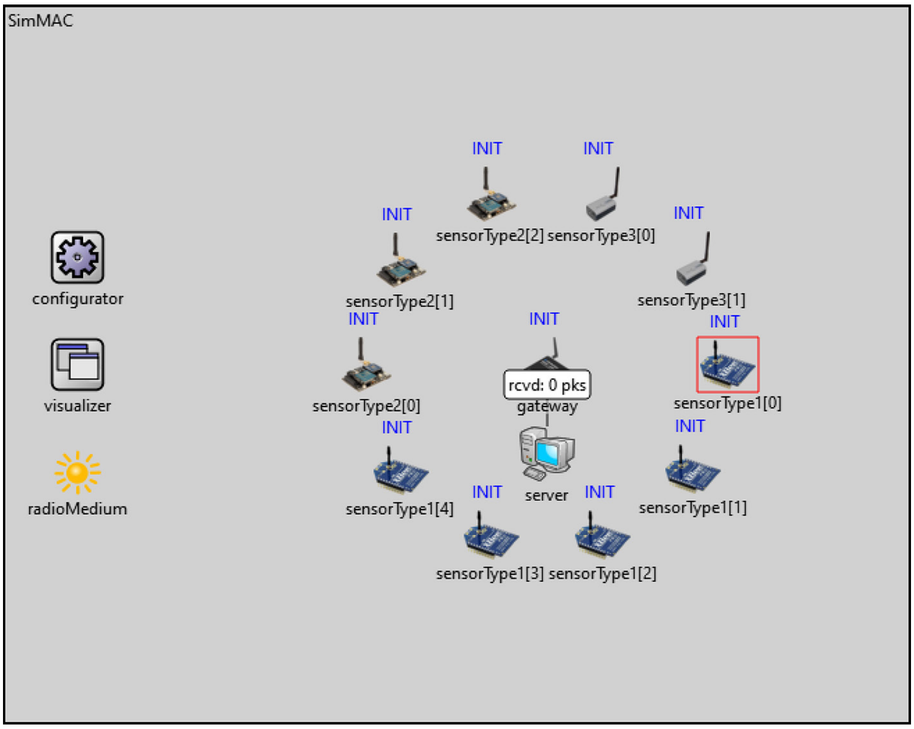

Figure 1. Sample network model

Based on the study, it was determined that the worst average packet delivery correctness rate in the range studied was obtained for a gap of 0.01 s. In the range of 0.01–0.04 s, the correctness increased, while for the subsequent ones it gradually decreased. The highest average quotient was achieved for the B-MAC protocol with a slot length of 0.04 s.

The graph of the dependence of the average correctness of packet delivery on the length of the time slot for the X-MAC protocol has a more irregular character with visible sudden drops in correctness. For the initial values of the parameter (up to 0.04s) in all networks none of the sent packets reached the server. By far the best average result (19.6%)) was achieved for a time slot equal to 0.07s. In the case of the L-MAC protocol, for the examined range of parameter values, the graph had a very regular character and a gradual decrease in average correctness was observed as the length of the time slot increased (except for 0.13 s). The best result (about 29.3%) was obtained for a slot equal to 0.05 s.

To verify the correctness of the selection of the best value of the parameter, simulations of networks containing from 5 to 20 sensors were carried out in two variants: based on the protocol with the selected and the default slot length. The results of simulations of the correctness of packet delivery for each protocol are shown in Figures 3, 4, and 5.

Based on the visualization, it can be seen that for smaller networks better packet delivery accuracy was obtained for the default time slot length. However, for networks with 7 sensors, the B-MAC variant with a gap of 0.04 s was slightly better -62.3% to 61.1%. For larger networks, however, unquestionably better results were obtained for the selected value of the parameter. In the case of the X-MAC protocol, a clear difference can be seen in the achieved correctness of packet delivery for the default and selected time slot length. Using the default variant, the best correctness was obtained for a network with 5 sensors and it was about 10.6%. For the same network size, the protocol with a selected slot yielded a result of about 83%. It can be observed that as the number of sensors in the network increases, the correctness of packet delivery decreases. For 20 sensors in the case of the better protocol variant, about 14% of packets reached the server (2.5% in the worst case).

The variant of the L-MAC protocol with a selected slot length achieved better reliability for all tested network sizes. For the default value of the parameter, the best result was achieved for the network with 6 sensors and was about 10%.

	slot_duration	mean_packets_received_ratio	mean_energy_utilization
1	0.01	0.0009476101	49.49797
2	0.02	0.1917094099	49.40502
3	0.03	0.3040834521	48.77177
4	0.04	0.3107947107	47.53357
5	0.05	0.2931170160	46.57795
6	0.06	0.2705437544	46.15057
7	0.07	0.2566303487	46.12994
8	0.08	0.2357511364	46.57731
9	0.09	0.2271734071	47.62445
10	0.10	0.2152381727	48.24799
11	0.11	0.2022372494	49.64567
12	0.12	0.1850258122	50.51764
13	0.13	0.1889009783	52.16166
14	0.14	0.1719861415	53.29163

Figure 2. Sample network model

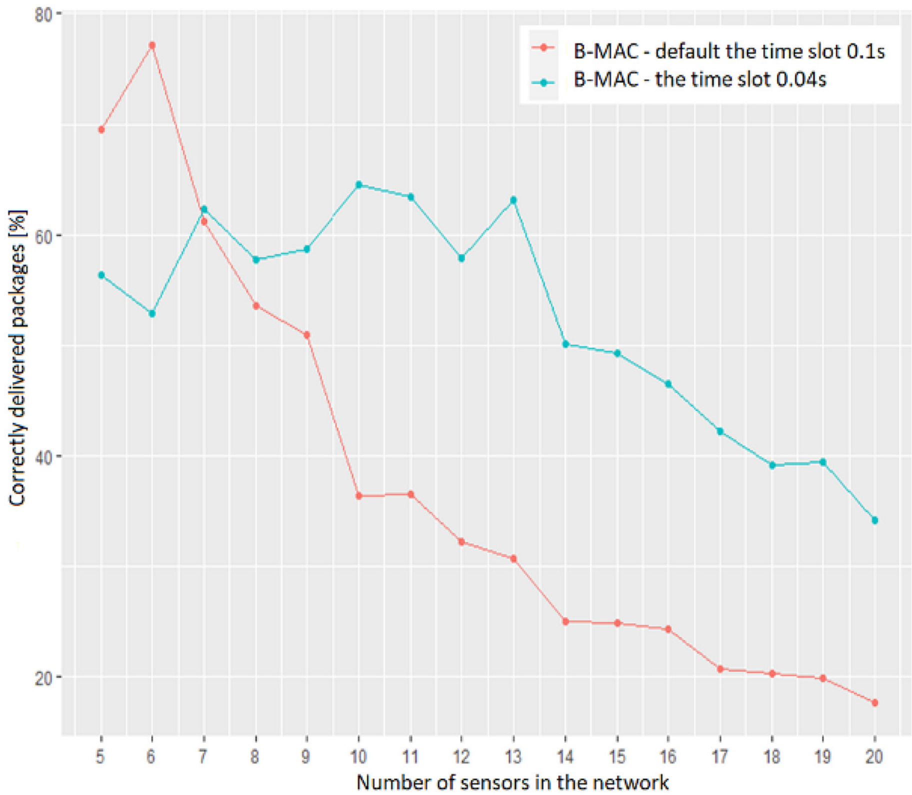

Figure 3. Packet delivery correctness simulation results for B-MAC protocol

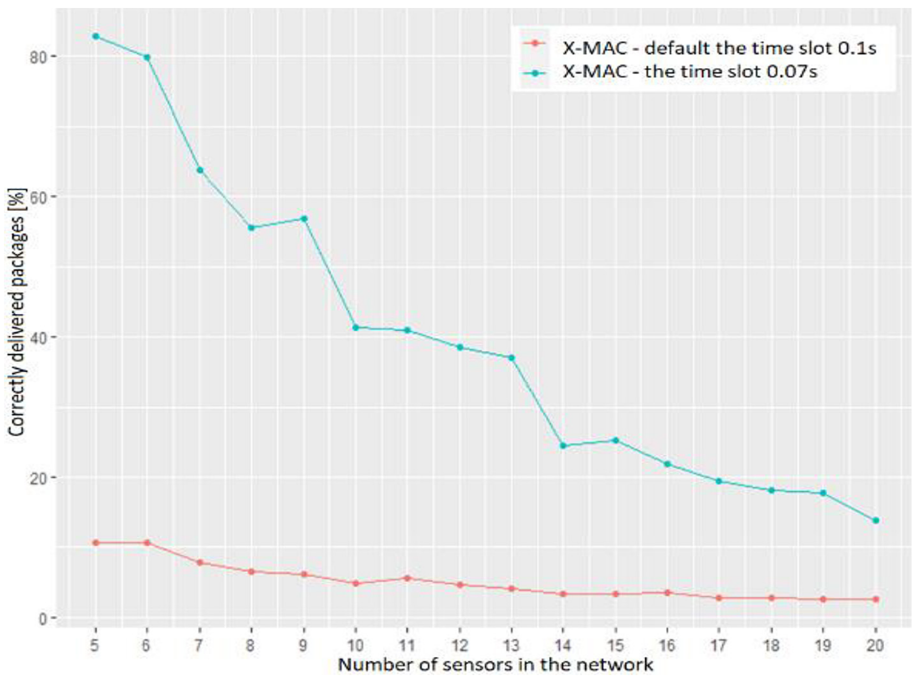

Figure 4. Packet delivery correctness simulation results for X-MAC protocol

In contrast, the worst result for the second variant was approx. 47.8% (17 sensors), and the best is about 94.1% (6 sensors). It can be noted that the graph has a stair-step character manifested by clear decreases in reliability for 9 and 17 sensors. This is due to changes in the number of slots – for networks with the number of sensors from 5 to 8, the number of slots was 8, for 9-16 sensors it was 16, and for 17-20 sensors it was 24. In the default configuration, on the other hand, the number of slots was 64. In most cases, a significant improvement in reliability was achieved

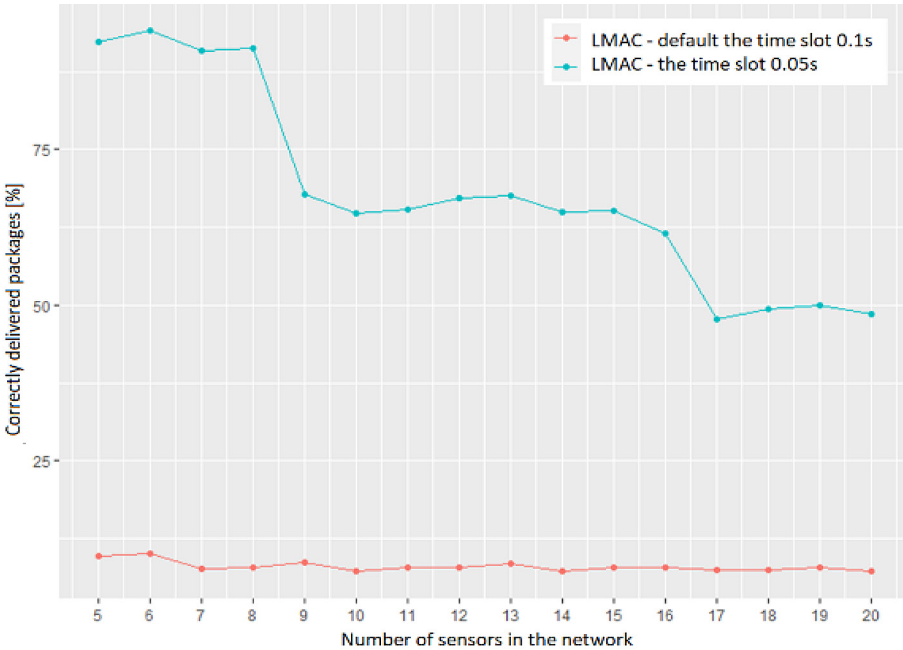

Figure 5. Packet delivery correctness simulation results for L-MAC protocol

compared to the default value of the parameter. Figure 6 shows the comparison of packet delivery correctness rates obtained in simulations of the studied data link layer protocols.

From the graphs in Figures 7, 8, and 9 it can be seen that for all network sizes considered, the L-MAC protocol had the best transmission reliability. However, comparing X-MAC and B-MAC protocols between each other, it can be concluded that for smaller networks (up to 7 sensors) better results were obtained using the former. As the network size increases, however, the correctness of packet delivery decreases much faster for the X-MAC protocol, and it is the use of the B-MAC algorithm that proves to be a better solution. The B-MAC protocol with the parameter value determined earlier as the best in terms of transmission reliability allowed to achieve lower

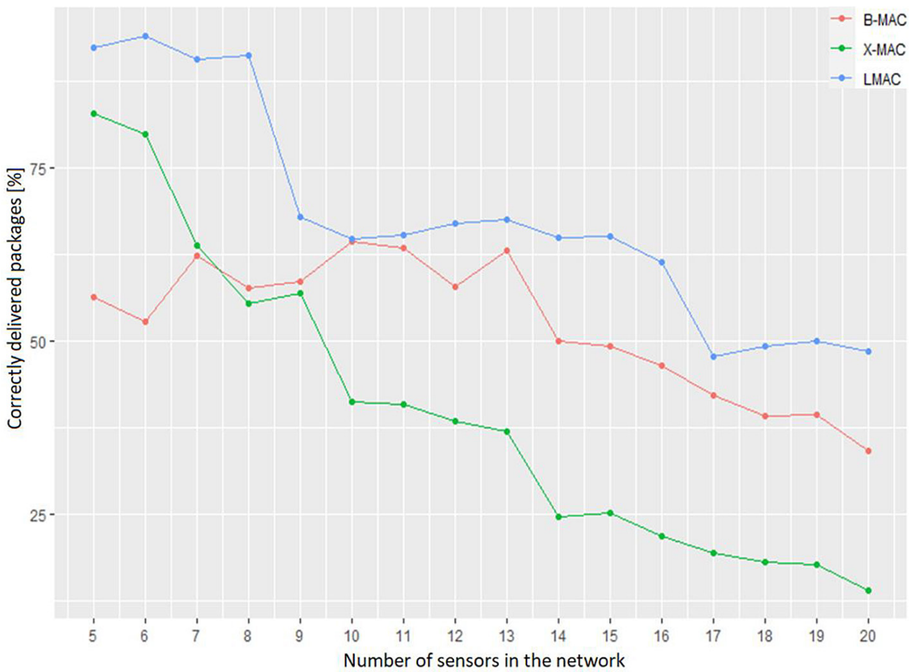

Figure 6. Summary of the correctness of packet delivery for analyzed protocols

energy consumption in smaller networks (up to 9 sensors), in other cases less energy was consumed using the default configuration. The average consumption for a slot of 0.1 s was 16.1 J, while that of 0.04 s was 17.4 J. The difference may be due to the fact that nodes controlled by the default variant of the algorithm checked the channel occupancy status less often.

The average consumption of energy resources by the X-MAC protocol with the default time slot length of 1s was 12.7 J, while for the selected length of 0.07 s, it was 11.5 J. Thus, it turns out that the selected protocol variant achieved both a higher packet delivery ratio and lower overall energy consumption. This may be due to the fact that there are more packet collisions and retries in networks based on the default configuration of the X-MAC algorithm. In the default L-MAC configuration (64-time slots of 0.1 s), the average consumption

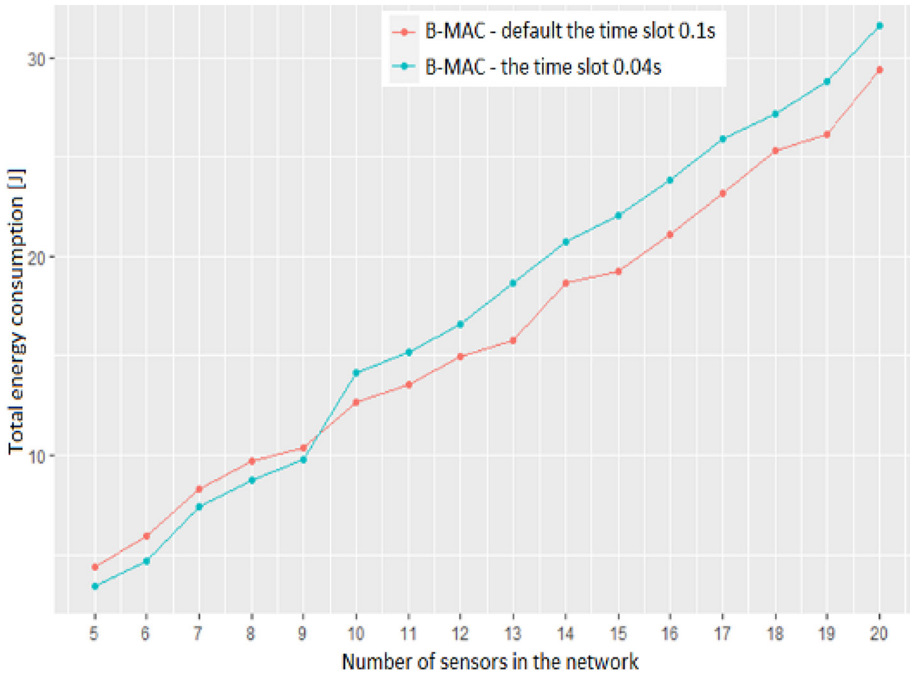

Figure 7. Energy consumption for B-MAC protocol

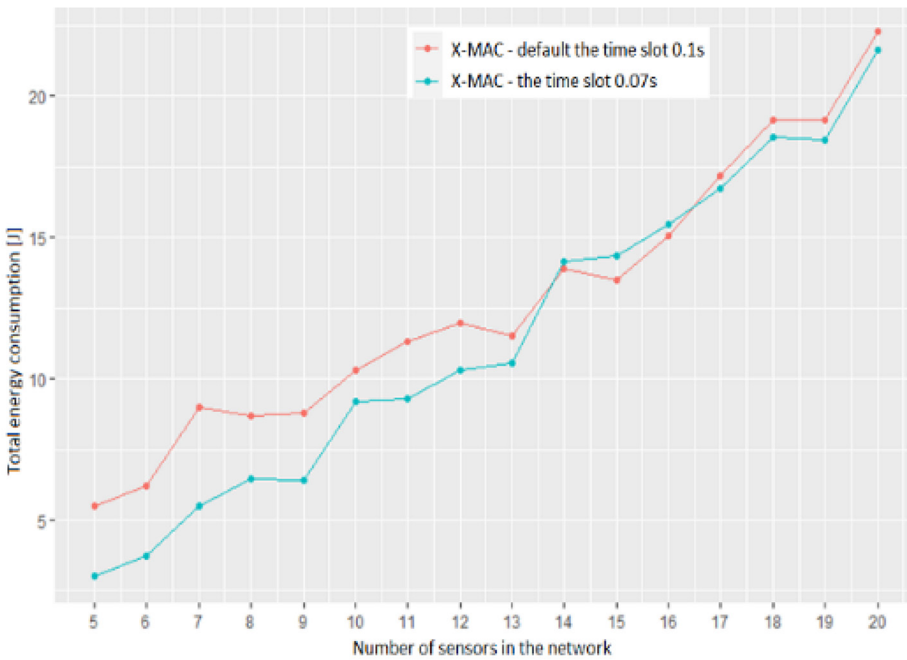

Figure 8. Energy consumption for X-MAC protocol

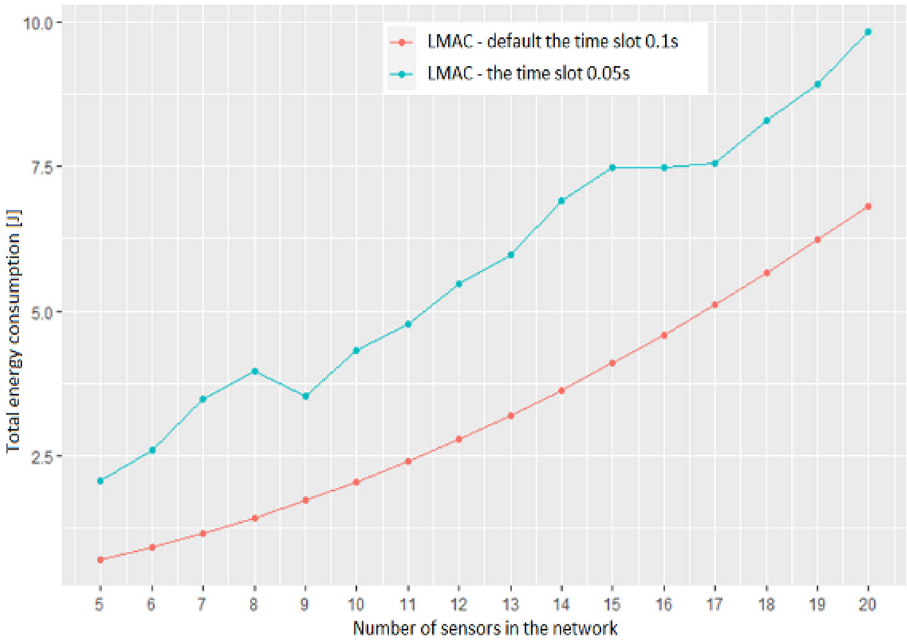

Figure 9. Energy consumption for LMAC protocol

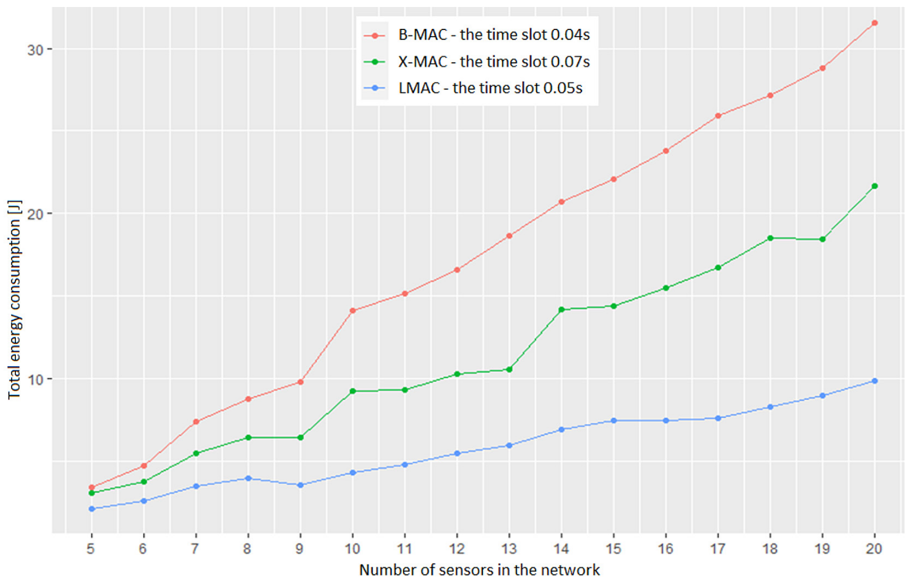

Figure 10. Consumption of energy resources as the number of sensors in the network changes

was 3.3 J, while in the modified version (the number of slots depending on the size of the network, each of 0.05 s), networks consumed an average of 5.8 J of energy. The higher consumption in the second case may be due to more frequent changes in the activity state of nodes resulting from a larger number of transmission windows - nodes enter activity mode at the beginning of each window to check whether packets are to be sent to them. Figure 10 shows how the consumption of energy resources by the tested protocols develops as the number of sensors in the network changes. From it, it can be seen that in each case tested, the L-MAC protocols consumed the least energy resources of the nodes, while the B-MAC protocol was the least energy-efficient. The average power consumption for the B-MAC protocol for the tested network size range is about 17.4 J, for the X-MAC protocol 11.5 J, and L-MAC 5.8 J.

The performance of a standard WSN is dependent on the MAC protocol used, so design factors should be carefully adjusted when implementing a specific WSN. Classical MAC protocols were originally designed for applications handling only scalar data while the implementation of MAC protocols in WSNs is strongly related to the requirements of the applications supported by the sensor nodes [20-24]. This is still an important and ongoing problem that many researchers are tackling with similar results to those indicated in this publication. Authors in [23] proposed a new protocol - Optimized Compressed Sensor Routing Protocol (OCSRP), which performs multimedia data routing in a highly efficient manner, which can solve the above-mentioned research challenges such as resource constraints and QoS. The results were compared with the LEACH algorithm, as the most widely used so far. In the publication [20], the authors emphasize that the problem to be solved is the lifetime of wireless sensor networks, which is completely determined by the energy consumption of the nodes. Therefore, sensor nodes must spend their energy wisely. The results obtained by the authors showed that it is necessary to design new or modify existing media access control techniques in such a way as to be able to save energy in wireless sensor networks. The authors showed that after analyzing the performance of the Routing protocol under different network conditions, PMAC had a higher PDR ratio. On the other hand, ALOHA spent the least time on routing parent packets, which allowed it to significantly increase the network survivability while using the least amount of battery power. On the other hand, PMAC (Prioritized Medium Access Control) and TMAC (Timeout MAC) show modest performance in the entire network. PMAC effectively eliminates data collision and optimizes channel allocation. Moreover, as many networks nowadays compose traffic with several priorities, the simple yet effective design of PMAC offers strict service differentiation for prioritized packets. Aiming at meeting the requirement of high energy efficiency monitoring of WSNs in noisy environments, a hybrid routing algorithm based on Naïve Bayes and improved particle swarm optimization algorithms is proposed [24].

In HRA-NP (a hybrid routing algorithm based on Naïve Bayes and improved particle swarm optimization algorithms), sensor nodes are grouped to form balanced clusters using the Naive Bayes algorithm. A new fitness function is designed to evaluate the solutions generated by the PSO (Particle Swarm Optimization) approach. Poor channel utilization is another problem associated with TDMA-based MAC, which can be improved by using the slot-stealing technique. The considered hybrid MAC protocols try to combine the strengths of CSMA and TDMA-based MAC protocols while compensating for their limitations to achieve better performance in dynamic traffic patterns. An important conclusion of the authors [20] from this study is that many WSN MAC protocols are designed without considering the impact of the network layer on the overall system performance. Integration of the layers may be an open research topic. MAC protocols for EH-WSN (Energy Harvesting -WSN) must support adaptive duty cycle for individual nodes based on their available energy, which may be a potential research area. As Khan [21] emphasizes once again, changing the threshold parameter values has a significant impact on the performance of MAC protocols in WSNs. In ADP-MAC, the optimal CVT value was identified by conducting test evaluations for three types of arrival schedules. It was shown that if the threshold value is not selected efficiently, the performance of the MAC protocol can be significantly degraded.

As the paper highlights, the performance of a standard WSN is dependent on the MAC protocol used, so design factors should be carefully adjusted during the implementation of a specific WSN. The present study can help select appropriate solutions considering the number of nodes, traffic volume, network coverage size, and mobility of nodes aiming to achieve an efficient WSN with an optimal energy consumption ratio. Changing the threshold parameter values has a significant impact on the performance of MAC protocols in WSNs. MAC protocols for EH-WSN (Energy Harvesting -WSN) must support adaptive duty cycle for individual nodes based on their available energy, which may be a potential future research area. The obtained research results are consistent with those published by other researchers [4, 20-24]. Comparing the overall performance in several aspects (such as node energy consumption, network throughput, and communication delay), the X-MAC protocol shows significant advantages and can be easily implemented on nodes supporting packet-switched wireless transmitters.

CONCLUSIONS

The paper shows how to use a network traffic simulator called OMNeT++ to generate data describing the operation of sensor networks based on different protocols. Simulations of networks in a star topology of different sizes using B-MAC, X-MAC, and LMAC data link layer protocols were created, and the resulting data were then analyzed in the R programming environment.

In the case of data link layer protocols, the effect of changing the value of the time slot duration parameter on the correctness of packet delivery was studied. In the context of the B-MAC and X-MAC protocols, which are based on the CSMA mechanism, this parameter denoted the duration of the time window for a node to stay in sleep mode. For the L-MAC protocol, on the other hand, which is based on the TDMA mechanism, this parameter determined the duration of a single transmission window (media access time). In the study, reliability was taken as an indicator of the quality of the protocol variant, but it should be borne in mind that a longer time slot length often means greater consumption of nodes' energy resources. It may therefore be necessary to use a protocol that allows a compromise between the correctness of packet delivery and energy requirements. However, comparing among themselves the efficiency of specific variants of the B-MAC, X-MAC, and L-MAC protocols, it turned out that the best transmission reliability for all considered network sizes allowed us to obtain the L-MAC protocol. This algorithm also proved to be the most energy-efficient.

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