INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2020, VOL. 66, NO. 1, PP. 93–98
Manuscript received November 15, 2019; revised January, 2020. DOI: 10.24425/ijet.2019.130270

Dense Wireless Network Inspired by the Nervous System

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***Abstract*—This work presents concepts of the use of algorithms inspired by the functions and properties of the nervous system in dense wireless networks. In particular, selected features of the brain consisting of a large number of nerve connections were analyzed, which is why they are a good model for a dense network. In addition, the action of a selected cells from the nervous system (such as neuron, microglia or astrocyte) as well as phenomena observed in it (e.g. neuroplasticity) are presented.**

***Keywords*—dense wireless network, nervous system, neurons, glial cells**

I. Introduction

The increase of the demand for wireless services is directly related to the issue of the more efficient use of available spectral resources. In this context, it is worth paying attention to two directions of research aimed at ensuring stable access to services for many users. The first direction leads to the idea of thickening the wireless network and reducing the distance between the transmitter and receiver (e.g. by creating heterogeneous networks with many so-called small cells or by using ad-hoc or sensor networks) [1] [2]. The second direction, however, is heading towards the introduction of an ever increasing level of intelligence into wireless networks - this is a trend observed especially in relation to radio technology and cognitive networks or SDN (Software Defined Networks). As a result of research work, wireless networks are becoming - colloquially speaking - increasingly dense and providing an ever higher level of self-organization (in a sense, autonomous) [3].

The above observation has become the reason to look for analogies between dense (or very dense) networks and solutions existing in nature. Observing the life and functioning of living beings, in particular human beings, one should wonder how it is possible to perform many, often simultaneous and complicated operations without feeling more tired. A deeper analysis of human physiology emphasizes the enormous role of the brain and the entire nervous system, without which it would not be possible to perform any vital functions (starting with moving, thinking, creating, or even such basic functions as heartbeat or breathing). It can be said that the nervous system controls every element of the human body. At the same time, the nervous system uses only a small portion of the energy consumed by humans, and moreover, it has the ability to adapt to a new situation or regeneration after illness or accident. In addition, mechanisms functioning in a healthy nervous system provide measurably very high reliability in the transfer of information. Inspired by such high energy efficiency of the brain and nervous system in the context of a huge number of tasks performed and a huge number of system components (nerve cells), the article presents the way in which selected functions of the nervous system can be used in wireless communication. The main assumption adopted in the work is an attempt to introduce mechanisms operating in the nervous system into a very dense wireless network (of the order of at least one node per square meter). An additional assumption is striving to minimize the power consumption of the devices in the network and ensure reliable transmission (e.g. in the order of 99.999 %). It seems that obtaining such parameters may be achievable by using inspirations derived from the human nervous system.

The work first presents selected elements of the nervous system and brain, and shows their characteristic features, pointing to biology-inspired applications in wireless communication each time. Next, the model of the simulated system is described, in which the described inspirations are implemented, and the results of the obtained research are presented. The whole work is summarized in the last chapter.

II. Nervous System

The nervous system consists of two main categories of cells: neurons and glial cells. Basically, the role of neurons is to transfer information, and the role of glial cells is to support this transmission. Billions of such cells form a central and peripheral nervous system that transfers information between various other parts of the body. This enables, among others, movement, learning and the use of the senses (sight, hearing, smell, taste and touch). The nervous system also controls human vital functions (e.g. heart muscle), so it is essential in our lives. In addition, it is interesting from the point of view of communication, because it is a very large (billions of cells) and dense network, with a lot of connections [4].

The nervous system through human life changes and optimizes its operation. During the human perinatal period, the nervous system is only partially connected and consumes a large part of the energy consumed by the child. In childhood, when people learn many basic skills, such as movement and speaking, a rapid increase in the number of neural connections can be observed. After puberty, the nervous system is only responsible for about 20 percent of the energy consumed by the body, despite the fact that adults have well-developed skills and intelligence. This means that the nervous system can very

The presented work has been funded by the National Science Centre in Poland within the “BioNets”project (no. 2016/23/B/ST7/03937) of the OPUS programme.

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effectively optimize its own energy consumption, which is very important in wireless communication. In addition, if part of the nervous system is damaged in the event of an accident or illness, there is a chance that rehabilitation will restore lost skills as a result of rehabilitation. In terms of repair algorithms, this is a topic worth researching. It should be emphasized that, despite great scientific progress, the exact functioning of the nervous system and the phenomena occurring in it are not fully known and understood. However, even with the current state of knowledge, a lot of inspiration could be taken from the nervous system and applied in wireless networks. The following subsections present selected elements or features of the nervous system that have proved useful or interesting from the point of view of wireless communication. The inspirations presented do not exhaust the issue and are just an example of practical application.

A. Neurons and Neurotransmitters

The basic cell in the nervous system is a neuron or nerve cell. It plays a key role in processing and transmitting information. The neuron consists of a cell body, dendrites, axons and synapses. Communication between neurons is possible using chemical compounds (called neurotransmitters) and electrical impulses. Information transmitted by various neurotransmitters can be received by nerve receptors in neuronal dendrites. When enough neurotransmitters are received, the neuron can generate action potential (electrical impulse) in the axon hillock. If the action potential is high enough, it can propagate along the axon. When action potential reaches the end of the axon, synapses can release new neurotransmitters, which in turn can be picked up by subsequent neurons. Different types of neurotransmitters can stimulate or inhibit further neurons. Basically, three types of neurons can be distinguished: motor neurons, sensory neurons and inter neurons. Motor neurons are found e.g. in muscles and allow muscle contraction. Sensory neurons are found in the skin, for example, and allow you to feel your touch. An inter neuron is a type of neuron that connects to other neurons. Neurons are also responsible for thoughts, dreams and intelligence.

Inspiration: A neuron can be represented as a simple wireless node. It has the ability to transmit (neurotransmitters as radio transmission and reception, action potential - information or message), processing (cell body - processor, axons and synapses - radio wave emission). Neurotransmitters can also simply be reflected as different types of statements, data or messages.

B. Neuroplasticity

Neuroplasticity is a phenomenon observed in the human body during which the entire nervous system optimizes energy consumption. Children before birth have a partially connected network of neurons. Then during adolescence, the nervous system both creates new nerve connections and loses some of the unnecessary (excess) connections in the process of synaptic pruning. As a result of this optimization, the energy consumption of the nervous system in relation to the total energy consumption of the body is reduced by 2 to 4 times. In general, this process ensures better functioning of the entire nervous system, especially the brain. The term neuroplasticity also includes path changes (connections) in the event of illness or accident. This means that a damaged part of the nervous system can be omitted, and a different path for a given information will replace this missed path [5].

Inspiration: In a wireless network, neuroplasticity can be implemented as a learning mechanism that introduces some tolerance to errors. For example, this function can be implemented by changing the forwarding route in case of capacity problems with some paths or in the event of a network node failure. Of course, in the field of communication, the time scale of this repair process should be changed, which cannot include weeks or months as it does in the human body, but the general idea is still worth considering. Another way to use neuroplasticity in a dense wireless network is to optimize energy consumption across the entire network. An example application may be the use of a dynamic routing algorithm and the use of switching devices to sleep mode, if there is currently no need to use them (as well as cutting connections in the human body).

C. Myelin Sheath

Myelin is a substance built mainly by lipids. It is formed in the form of an axon sheath by oligodendrocytes in the central nervous system and by Schwann cells in the peripheral nervous system [6]. The main function of the myelin sheath is to isolate the action potential that propagates through the axon. It also speeds up the transmission of pulses, which is crucial from the point of view of signal propagation. When the action potential travels through the axon without the myelin sheath, the signal suppression is more likely. Thus, it can be said that myelin provides a faster and more reliable propagation path for impulses. To highlight the importance of myelin in the human body, you should look at demyelinating diseases such as multiple sclerosis. Diseases of this type are characterized by myelin breakdown or defects that provide typical symptoms such as sensory or motor disorders, vision and speech problems. All these symptoms are related to problems of signal propagation between neurons.

Inspiration: In wireless communication it is not possible to accelerate the transmission using electromagnetic waves between specific points. However, there can be reduced the transmission delay in a multi-hop network by reducing the number of hops (e.g., by using more transmit power). The myelin isolation function can be implemented using better encoders or data protection methods, which is equivalent to ensuring that the specified transmission can be more reliable. In addition, it is possible to use e.g. beam shaping or directionality of the antenna to improve signal quality, and thus minimizing the likelihood of retransmission.

D. Oligodendrocyte and Schwann Cell

Oligodendrocyte and Schwann cell are glial cells whose main function is the production of myelin sheaths on axons that ensure their isolation [7]. The process of creating the myelin sheath is called myelination. The oligodendrocyte is found in the central nervous system and forms a myelin sheath on up to 50 axons. The Schwann cell, in turn, is located in the peripheral nervous system and forms a myelin sheath on single axon. Myelination begins before birth and continues until adulthood (up to 30 years old). This process in the infancy period is very fast, which is associated with the development of motor or cognitive skills (such as walking, speaking and understanding of language). Myelination slows down in adulthood, but it doesn't stop. This process can be considered as a learning phase of the nervous system.

Inspiration: Myelination provided by oligodendrocytes and Schwann cells can be implemented as a network's ability to learn. At first, the network (distributed dynamically and randomly, such as in ad-hoc networks) must collect some data to get started. However, this process does not stop because the network may adjust some parameters during operation. This function can be implemented as a long-term control layer.

E. Blood-Brain Barrier and Astrocyte

The nervous system is separated from the blood circulating in the human body [8]. However, there are mechanisms that allow the blood to affect the nervous system. Directly at the interface of blood vessels with the central nervous system is the so-called Blood Brain Barrier (BBB). From a communication perspective, the most important part of this barrier is a glial cell called an astrocyte. The smallest blood vessels are surrounded by astrocytes. Astrocytes can detect some chemicals in the blood (e.g. glucose) through specialized receptors. Using this knowledge, astrocytes can communicate with each other and affect transmission between neurons without the decision of the central nervous system. It can be said that the blood-brain barrier connects two systems (or networks) at the same time, allows some communication and at the same time ensures separation between them.

Inspiration: In a wireless network, the blood-brain barrier can be interpreted as a decomposition of the control layer and the data layer. In another context, however, this barrier can be understood as the coexistence of different networks side by side (e.g. LTE networks, WiFi and sensor networks). The astrocyte function can then be treated as a virtual switch at the interface of two networks. This means that some parameters of one network may affect the functioning of another network. For example, the detection of a sensor network in a certain location in an emergency (e.g. flood risk) can help another network respond appropriately. In the event of a sudden power failure, this information can be used to reroute the traffic so as to bypass the location and thus reduce the likelihood of a connection failure. In other words, this function can be implemented as a short-term control layer that can reconfigure part of the network in an emergency.

F. Microglia

Microglia is another very important glial cell in the human nervous system. This is the first and main form of active human immune defense in the central nervous system. Microglia cleans the brain of unnecessary and damaged neurons or cells. It can occur in two forms: resting form when observing the environment and active form when taking action. What is very important - microglia can communicate with other microglia cells, astrocytes and even neurons [9].

Inspiration: In the wireless network, many useful applications of microglia can be found, such as ensuring tolerance to network errors. The simplest solution is to create a separate device that observes the environment (e.g. power level, interference, packet flow) of the given network and in the event of significant changes (e.g. sudden loss of response from one of the devices) can react. This device can react in several ways. First, it can inform other devices, the administrator or network controller. Additionally, it can take over tasks that have been performed by the currently unresponsive device. The microglia functionality in this case is very similar to the functionality of the astrocyte, but the microglia-inspired device is a device working inside a given network, and the astrocyte-inspired device is an external access to the network.

Using the abovementioned elements of the nervous system and phenomena occurring in it, the concept of dense wireless network using the above inspirations was presented.

III. SYSTEM MODEL

In the simulations carried out, a dense wireless network is considered, on whose edges there are users exchanging messages with each other. Due to the short distances between devices, it was assumed (intentionally to better express simple communication between neurons) that were no coding algorithms and it was assumed that the wireless channel would be modeled as a channel with a direct line of visibility (and corresponding attenuation of free space) along with white Gaussian noise AWGN. The following system parameters were also adopted: carrier frequency 2.45 GHz, 5 MHz system band, threshold for correct reception of SNR_{min} messages = 5 dB (if the received signal strength was lower, the message was treated as unreadable and was not transmitted; no algorithm of retransmission was used). The analyzed area contains a total of 120 network nodes, of which 99 are N-nodes, 20 are M-nodes, and 1 is A-node (the given types are described in the further part of the chapter). Exemplary positions of devices expressed in units of measurement are shown in Fig. 1.

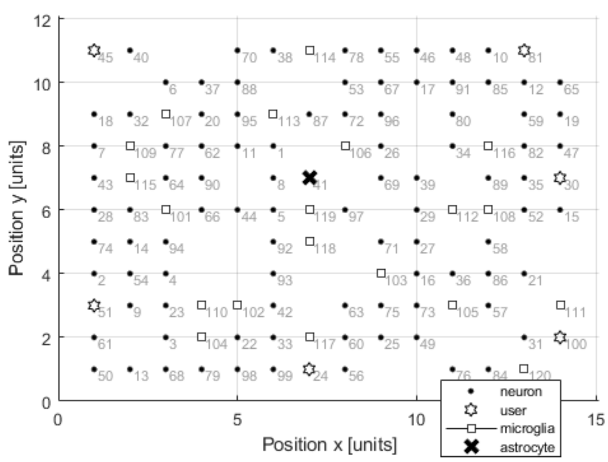

Fig. 1. Topology of simulated network

The use of units of measurement is a deliberate procedure leading to the independence of results from physical values. In the drawing we can see four types of devices: a neuron that represents a simple network node; user, i.e. a neuron that is on the edge of the analyzed network and sends and receives messages; astrocyte, that is, a device that sends instructions for changing power to nearby devices; and microglia, which is a device that is in the state of observation and under certain conditions joins the data transmission.

A. *The Routing Algorithm*

Due to it was assumed that the architecture of the network was unknown when the network was unfolded, the LoadNg (The Lightweight On-demand Ad hoc Distance-vector Routing Protocol) on-demand routing protocol used in Ad-hoc networks was used in the presented wireless network simulator. For the purpose of implementing the neuron's variable transmit power, forced by an astrocyte, the routing protocol has been modified. Each recorded path originally contained the target node index, the nearest node index through which you can reach the destination node, and the measure (distance) value of the path. An additional transmit power value has been added to the saved path, which can be sent inside the Route Request (RR) message. This value is necessary so that devices on the edge of the part of the network that uses less power with the edge of the part of the network that uses more power can use sufficient power to deliver the message.

B. *N-node*

It was assumed in the simulations that the primary network node (N-node) is inspired by the operation of a neuron. This means that it has the ability to receive, process and send information. In addition, there is the possibility of some learning, which is represented here by the dynamic routing algorithm.

C. *M-node*

Another type of device on the network is the M-node, which in turn is inspired by the operation of microglia. It is an N-node that initially does not actively participate in data transmission, but only observes its immediate environment. When it receives a message about a Route Error (RE), it activates its transmission capabilities and behaves like an N-node - it participates in the transmission. Another way to activate the M-node is to observe several path search (RR) messages. The second activation method enables faster response to a network problem. M-node, as in the case of microglia in the nervous system, works as a form of repair (first reaction) after a problem in the network (failure of a given device). In addition, during the simulation it was observed that when a problem occurred, too many M-nodes were activated. In order to overcome this effect, an additional rule has been introduced that causes the M-node to return to the state of environment observation again, if it was not used for data transmission (the routing algorithm chose a path that does not pass through the given M-node). Thanks to this rule, there are no active M-nodes in the network that are not used in the transmission (which proved to be over-activated).

D. *A-node*

An A-node is a type of device on the network that is inspected by the action of astrocyte in the nervous system. It does not participate in the exchange of messages between N-nodes (just like an astrocyte does not participate in the exchange of information between neurons). However, it has the ability to affect the way information is sent by N-nodes by sending a request to change transmit power to nearby N-nodes. The A-node performs this operation based on observation of parameters not directly related to the network in which it is located. The stimulus for action (increasing the power of N-nodes) is, for example, observation or information about problems with access to electricity in a given area (e.g. failure due to strong winds). Information about this phenomenon sent to nearby N-nodes causes an increase in transmission power, and thus a decrease in the number of hops in this region, which leads to an increase in the reliability of such paths.

IV. Simulation Results

In order to confirm the validity of mechanisms operating in the human body, intensive computer simulations were carried out, in which selected selected inspections from the nervous system were tested (the authors tested all of the described inspirations, however, due to the limitations of the place of publication, it was decided to presentations of selected solutions). In the first step, a simulation of M-node operation and their impact on the functioning of the entire network was carried out. For this purpose, random switching off of N-nodes has been introduced (with a probability of 30 % a given node ceases its operation during the simulation). In addition, a random (exponential) selection of time after which the node will shut down has been introduced. The results of two simulation scenarios are presented below, where in the first one despite problems in the functioning of the network M-nodes do not start (blocked functionality) and in the second M-nodes have the ability to activate and join the transmission. In Fig. 2 you can see the time distribution between sending the message and receiving confirmation of receipt of the message for all network users.

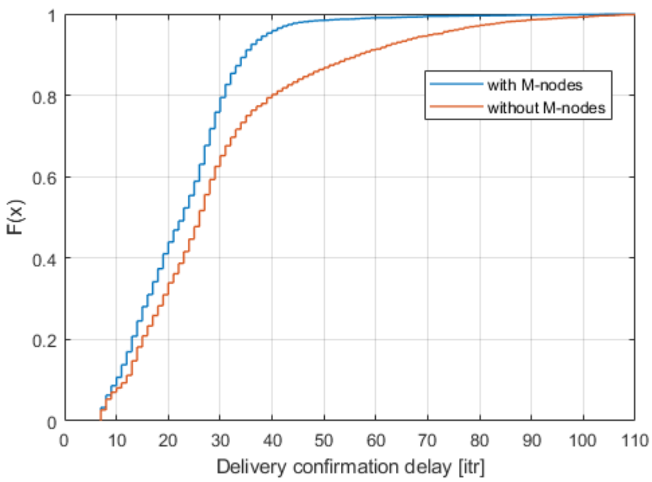

Fig. 2. Distribution of delivery confirmation delay

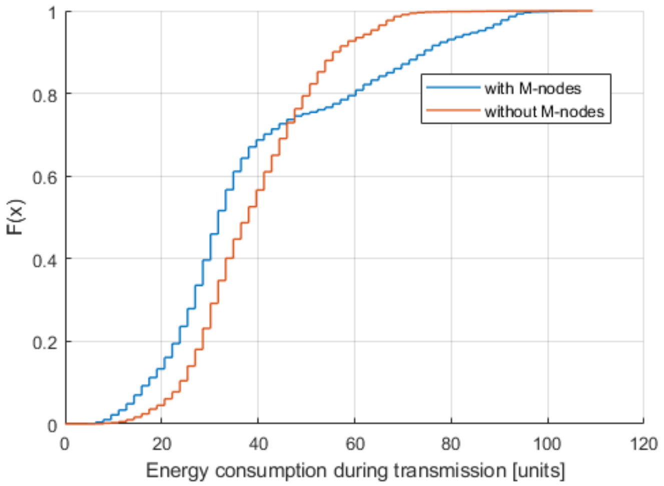

Fig. 3. Distribution of energy consumption during transmission

Fig. 3, in turn, presents the energy distribution used for transmitting messages across all network nodes during the entire simulation. Energy was expressed in terms of power units, which is a deliberate attempt to make the results independent of physical values. Assuming that the message is valid, if its receipt is confirmed within 40 moments of time, then if M-nodes are used, the probability of unserviceability is reduced by 10.77 percentage points. Analysis of the above results leads to the following conclusions. The use of M-nodes in a network can reduce the delay of transmitted messages, but more importantly reduce losses in a partially damaged network. However, this profit can be paid for by increased energy consumption by network nodes and, of course, at the expense of additional devices.

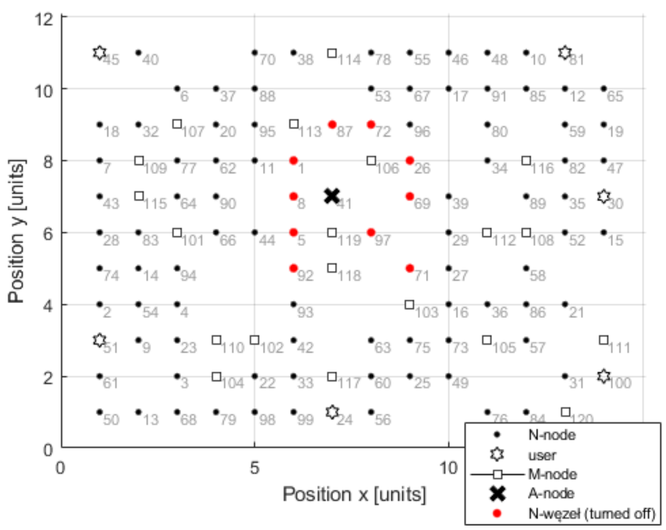

Fig. 4. Topology of simulated network (A-node)

Another analyzed scenario is a situation where there are problems with the operation of the network in a certain area, e.g. a power failure occurred in a specific place, and as a result individual network nodes stop working. In order to present a solution to this type of problem, one additional device (A-node) was introduced in this area, which after observing the problems (external information) sends to the nearest network nodes a command to change the power to a higher one. In the analyzed case, when all the nodes operate nominally with a power equal to 2 dBm, the A-node sends a request to change the power to 5 or 8 dBm. In this case, M-nodes were not used. Fig. 4 shows the topology of the analyzed network together with the N-nodes marked in red, which are switched off.

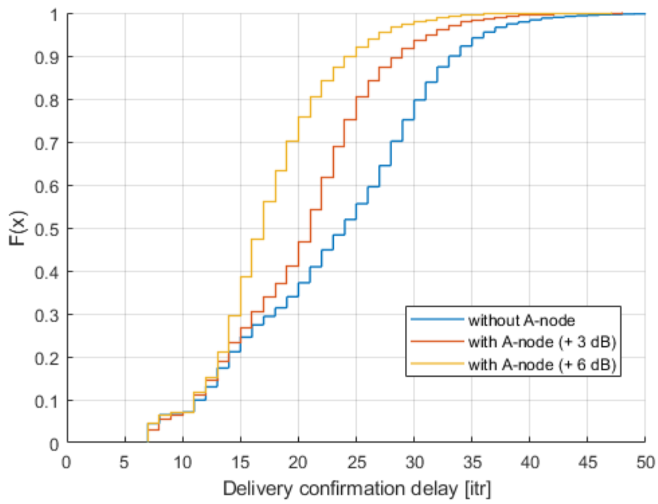

Fig. 5. Distribution of delivery confirmation delay (A-node)

Fig. 5 presents the distributor of delays of message delivery confirmation for a case where the A-node functionality is not used, as well as two cases where this functionality is used, increasing the power by 3 dB or 6 dB, respectively. From the analysis of this drawing, it can be seen that increasing power in the area where the problem occurs minimizes message delays in the network, while allowing "jumping" through the off part of the network (bypassing).

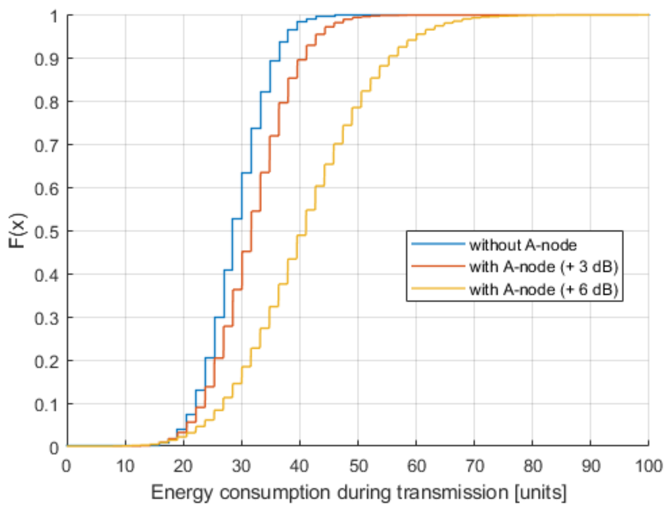

Fig. 6. Distribution of energy consumption during transmission (A-node)

Fig. 6, in turn, shows increased energy consumption during transmission. However, when using higher power, which allows to reduce the delay in the network, one should remember about the increased demand for electricity. It should be noted that the effectiveness of the proposed solution strongly depends on the network topology and location of N-nodes that will be damaged.

To validate proposed solutions authors evaluated also simulation of the different network. The analyzed network contains four times more devices (399 N-nodes, 80 M-nodes, and one A-node) over four times larger area (with the same density of devices). In Figure 7 and 8 we can observe the same behavior of the delivery confirmation delay distribution, as in case of the smaller network, for both M-node and A-node simulations.

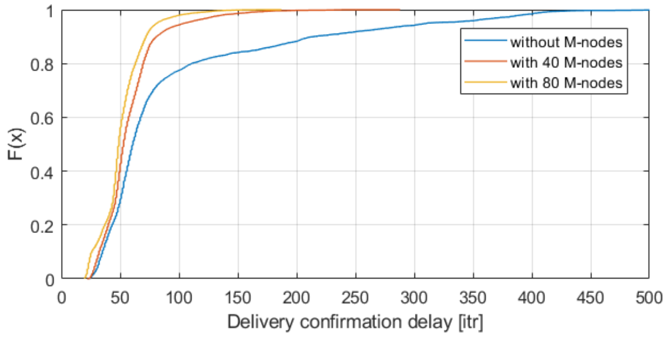

Fig. 7. Distribution of delivery confirmation delay (M-node) - larger network

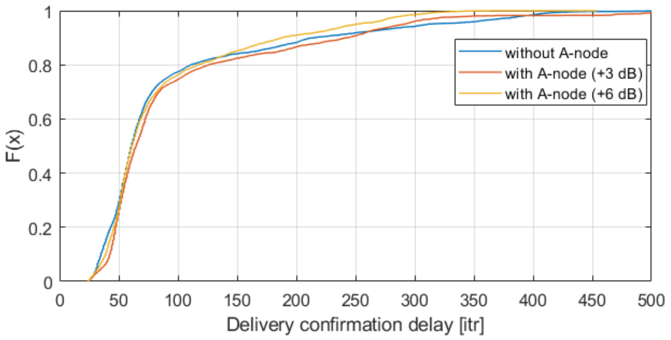

Fig. 8. Distribution of delivery confirmation delay (A-node) - larger network

However, in case of the energy consumption distribution in the larger network we can observe a lower energy consumption if we use a M-nodes in network, as we can see in Figure 9. This situation is caused by larger amount of the shorter paths between message source and destination if we use a M-nodes.

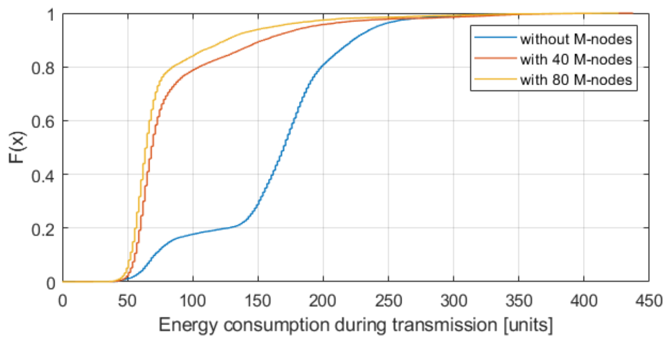

Fig. 9. Distribution of energy consumption during transmission (M-node) - larger network

In case of A-node simulation, we can observe in Figure 10 that the energy consumption distribution is very similar for the different power levels. The change of transmit power of only few N-nodes in center of the analyzed area influence a little on energy consumption in the whole network.

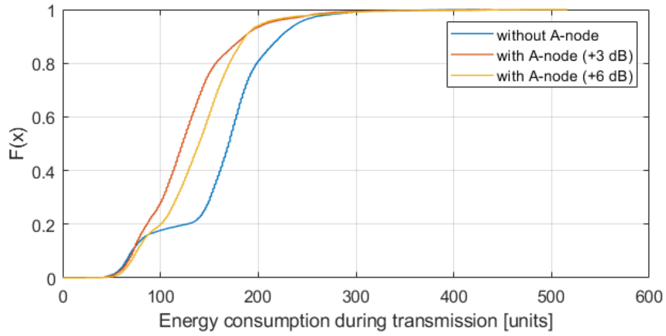

Fig. 10. Distribution of energy consumption during transmission (A-node) - larger network

V. Conclusions

In this work, several solutions found in the nervous system are proposed. The implementation of these solutions and appropriate simulations have shown that it is possible to use a device inspired by the operation of microglia in a wireless network that will improve the operation of the network in cases of failure. In addition, the possibility of using devices inspired by astrocyte, which can successfully influence the network and improve it, was pointed out. The analyzed area of science has many interesting and useful mechanisms that could be successfully used in wireless networks. The research results shown show that this is an interesting topic for further work.

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