Neuroplasticity and Microglia Functions Applied in Dense Wireless Networks

Łukasz Kułacz and Adrian Kliks

Faculty of Electronics and Telecommunications, Poznan University of Technology, Poznań, Poland

Abstract—This paper presents developments in the area of brain-inspired wireless communications relied upon in dense wireless networks. Classic approaches to network design are complemented, firstly, by the neuroplasticity feature enabling to add the learning ability to the network. Secondly, the microglia ability enabling to repair a network with damaged neurons is considered. When combined, these two functionalities guarantee a certain level of fault-tolerance and self-repair of the network. This work is inspired primarily by observations of extremely energy efficient functions of the brain, and of the role that microglia cells play in the active immune defense system. The concept is verified by computer simulations, where messages are transferred through a dense wireless network based on the assumption of minimized energy consumption. Simulation encompasses three different network topologies which show the impact that the location of microglia nodes and their quantity exerts on network performance. Based on the results achieved, some algorithm improvements and potential future work directions have been identified.

Keywords—*ad-hoc network, brain inspired communication, glial cell, neurons.*

1. Introduction

The human body has a great potential of adjusting itself to new, specific situations. There are various mechanisms which enable us to learn, become immune to disease and adapt to distinct settings. Such a straightforward observation could be, however, a source of great inspiration in realization of various network capabilities and features, such as learning capability, fault-tolerance, and self-organization. One may observe that almost all human functions are controlled or somehow affected by the central and peripheral nervous system. A closer look on these systems enables us to identify the neuroplasticity attribute which allows neural connections to adapt and reorganize. On the other hand, there are astrocytes which – among various functions they perform in the human body – join two separate, completely different systems enabling them to work together. Astrocytes are mainly involved in linking circulatory and nervous systems. Lastly, dedicated glial cells exist, with microglia being their peculiar type, having the ability to repair damaged neurons. Observations of all these features and capabilities of the human body (with the brain and the nervous system being their primary focus) lead to new proposals concerning their implementation in the context of dense wireless networks [1], [2].

In such a case, numerous transmission points (nodes), deployed randomly over the area concerned, transmit with relatively low power rating, thus communicating with their closets neighbors. The well-known examples include wireless sensor networks [3] and ad-hoc networks, widely explored over the past decades. In this work, however, we are targeting the problem of achieving high fault-tolerance (as may be observed in the human brain) in dense wireless networks, but based on two assumptions: that the overall amount of energy consumed is minimized to the extent possible, and that the complexity of communication between the nodes is reduced to the minimum required. Thus, one of the key assumptions is that the transmission power is minimized to a certain reasonable level (as discussed later), and that the number of nodes deployed within the network is large enough to model the link between the neighboring nodes as a line of sight with the dominance of additive white Gaussian noise (AWGN), and that the effect of multipath transmissions is neglected. Such an approach is necessary to relax the need for the application of advanced coding schemes and retransmission algorithms. We attempt to mimic the behavior of human brain whose energy efficiency in transmitting one bit of information is much lower than that of contemporary wireless systems, with a relatively high level of fault-tolerance being guaranteed.

In this paper we describe how a few inspirations based on the functionality of the human nervous system have been applied in the scenario considered, i.e. in a dense wireless network system, with the ultimate goal of achieving high reliability with ultra-low energy consumption. The paper is structured in the following way. First, in Section 2 we summarize the key capabilities and the selected features of the human brain and nervous system. In Section 3 we present our approach to potential implementation of these biological features in a dense wireless network. Simulation results are discussed and conclusions are drawn in Sections 4 and 6, respectively. Section 5 presents the authors' plan for the future in this topic.

2. Human Body Inspiration

In our investigations, we targeted highly energy-efficient and fault-tolerant dense wireless networks, where we at-

tempted to follow our overall inspirations based on the human brain and nervous system. In this section, we recap the biological and medical information about the roles played by selected *components* of the human body. We indicate precisely, how these *components* inspire us in the context of the scenario considered.

2.1. Neuroplasticity

The observation that human brain and the entire nervous system optimize energy consumption through the course of the entire life is the leading idea behind the research conducted. The brain of an embryo that is a couple weeks old has a fully connected network of neurons. Later, as a result of synaptic pruning, a small child's brain uses 44–87% of the total energy consumed by the body, whereas the brain of an adult – 25% at the most [4]. The process of maintaining commonly used neural connections and removing the rarely used routes is called *neuroplasticity* and ensures better performance of the human brain and lower energy consumption. In addition, in the case of injuries caused by illness or accidents, the brain is capable of rewiring the connections (after long rehabilitation). This means that it has the ability to bypass the damaged parts of the neural network and create new connections to restore the functions affected, e.g. feeling in the limbs. Fault-tolerance in that case is not instant, but requires much time. Although in a real-life wireless network a repair lead time that is too long is typically not acceptable, neuroplasticity still constitutes an interesting mechanism that is worth considering. It may improve the fault- tolerance ability of the network while keeping the overall energy consumption at the desired level.

From the point of view of wireless communications, neuroplasticity may be treated as the ability to optimize the functioning of the network, and to guarantee fault-tolerant communication in the case of an emergency.

2.2. Neurons

Neurons play an important role in nervous system of mammals. A neuron is made up of the cell body, dendrites and an axon with synapses at its ends. Dendrites receive neurotransmitters by receptors. In consequence, the neuron may generate the so-called action potential (AP) in the axon's hillock. This AP moves from the cell body, through the axon, to the synapses that release other neurotransmitters and may activate another neuron. That is how information is transferred within the nervous system. It is worth noting that this type of communication is unidirectional, meaning that where some impulses are generated, no reception of direct response is possible. To understand how the brain knows that some actions have already been performed (like moving or shaking one's head), one needs to note that all information between the central and the peripheral nervous system pass through the spinal cord. In the spinal cord, there are 31 pairs of spinal nerves and each pair is made of afferent and efferent nerves. Afferent nerves transfer impulses from *sensory* neurons (e.g. receptors placed in

the skin) to the brain. An analogy to uplink transmissions in wireless networks may be identified here. On the other hand, efferent nerves transfer signals from the brain to *motor* neurons, e.g. those placed in the muscles, which could correspond to the downlink transmission. Communication relying on afferent and efferent nerves is realized through different paths. This is why the same person may not be able to feel the touch with their hand, but may at the same be able to move their hand. Such symptoms may be the consequence of melanotic cancer, for instance [5].

The functioning of a neural network is continuously improved in the process known as neuroplasticity, which is based on a very simple rule: "neurons that fire together wire together" [6]. In this respect, a very important role is played by the myelin sheath which is formed on axons and ensures the acceleration of passing signals, as well as prevents unintentional leakage of impulses to other neurons. In simple words, myelin sheath protects information [7].

In the context of wireless networks, neurons may be treated as transmission points (nodes) responsible for the reception of and for relaying the message. Various neurons are responsible for different communication directions. Finally, the presence of myelin sheath may be understood as a way of boosting transmission in a specific direction and of protecting the information.

2.3. Microglia

Microglia are cells that play a key role in brain maintenance. They constantly monitor the neighboring (associated) neurons and eliminate the damaged or unnecessary neurons and synapses. Where a dangerous signal is detected, microglia switch into active mode. If the severity of the signal is moderate or low, they clean the debris, support regeneration and secrete substances needed in the process of remyelination [8]. But if the dangerous signal is intensive, microglia produce various types of substances to stop the cells that threaten neurons, and stimulate the production of new cells. Microglia are the primary form of the active immune defense system. It is also important to bear in mind that microglia have the ability to communicate with other microglia, nerves and astrocytes.

In the case of wireless networks, microglia may serve as a source of inspiration for creating specific devices which enabling the network to self-repair and activating in the state of emergency.

3. Bio-inspired Functions Applied in Wireless Networks

Once our inspirations originating from the particular elements of the nervous system have been presented and summarized, we intend to discuss, in the present section, details of the system model and the experimental scenario built based thereon. Selected algorithms have also been proposed and described.

3.1. System Model

It needs to be borne in mind that our ultimate goal is to investigate the solutions for wireless communications and data transfer, guaranteeing a high level of reliability with extremely low power consumption. The term *extreme* shall be considered in such a way that we intentionally want to eliminate all potentially unnecessary sources of power consumption. In particular, we intend to minimize processing in physical and medium access layers by relaxing the need for advanced message coding and decoding, sophisticated link adaptation, retransmissions, etc. Such an approach may be considered in a case where, for example, distances between the neighboring nodes are small enough to guarantee a line-of-sight transmission, and where the link may be effectively modeled as flat with AWGN dominance. In consequence, in this analysis we assume the presence of a dense network of simple (i.e. not complicated) wireless nodes deployed randomly over a certain area, and a set of users, also randomly placed on edges of this area, as presented in Fig. 1. Neurons are represented by distributed antenna systems consisting of four antennas (denoted in the figure by black dots), centrally connected by grey lines, and marked by ID. The neuron itself is described in detail in
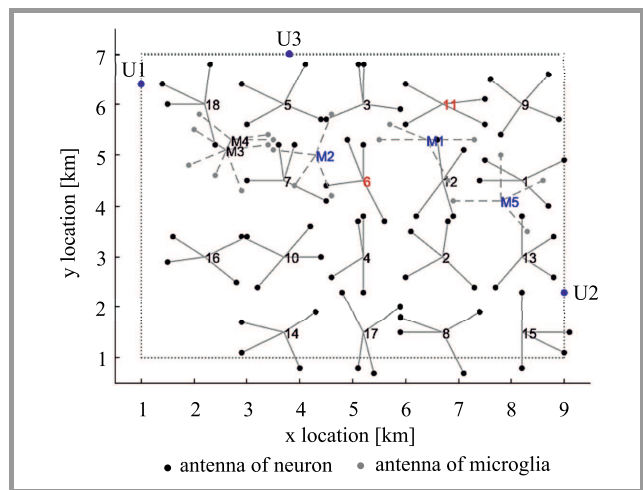

Fig. 1. Topology of the network considered: *Mi* denotes microglia nodes, blue color is used to represent those microglia nodes which will be used to repair the network, and red color is used to represent those neurons which will be considered as damaged. (For color pictures visit https://doi.org/10.26636/jtit.2019.130618)
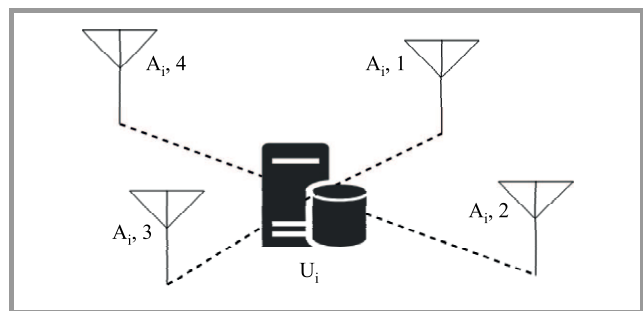

Fig. 2. A wireless neuron.

the following section and shown in Fig. 2. Microglia nodes are shown likewise as neurons, but are marked with grey dots. As black dots represent active antennas, grey color should indicate that microglia node antennas are not currently used for data transmission. Additionally, microglia nodes are marked by M prefix added to their ID. In our experiments, we are testing the behavior of the network in the case of various errors. Therefore, the neurons which will be considered damaged in later deliberations are highlighted by the use of red text. On the other hand, microglia nodes marked with blue text are the ones which will be used to repair the network. Users transmit messages between themselves, and the main role of the dense wireless network within the area considered is to forward data from the source user to the destination user. We assume that a unique ID is assigned to each user.

Following the analogy to the brain and nervous system, the considered network is composed of devices acting as wireless neurons and wireless microglia nodes (marked with the letter *M* letter before the index), as defined in the following subsections. By assumption, wireless neurons are very simple transceivers with learning (storing) ability - they can remember the approximate location of the user by associating their IDs with the nearest antenna. This information may be used to transmit data in the right direction, directly towards the specific user. The main goal of microglia nodes is to monitor the performance of the network. In the case of any network failure, these nodes may enable classic neuronal functionality (i.e. they can relay messages).

3.2. Wireless Neuron

Inspired by the functioning of the nervous system, we consider a transceiving device (we also refer to it as a wireless neuron) which mimics the behavior of a natural neuron. In particular, let us assume that *i*-th device n_i is equipped with a low-power distributed antenna system containing N_A antennas denoted as $A_{i,\#}$ and connected to the central processing unit U_i. An exemplary device with $N_A = 4$ antennas is shown in Fig. 2. The transmission power on each antenna is set to -1 dBm, and omnidirectional antennas are considered only. The wireless neuron is fired only when the strength (observed aggregated power) is above a certain threshold. Assuming constant noise power, this constraint may also be reflected by means of the minimum signal-to-noise ratio required, $\text{SNR}_{\min}$. Fulfillment of this requirement guarantees also that message dropping functionality, existing in the human brain as well, is applied too. Finally, such a wireless neuron is able to learn and adjust itself (following the neuroplasticity functionality) in order to reduce total energy consumption in the network and to send messages directly towards the destination node, as shown in Algorithm 1. Neurons use the myelin functionality to reduce unnecessary interference they induce within the network by selecting the antenna which is nearest to the destination user of the message. They also reduce energy consumption of the single neuron (the message is transmitted only by a subset of all antennas). In consequence, neurons

which are too far away from the best message route will not receive the message, thus the interference level will be reduced.

Algorithm 1: Neuron learning algorithm

   Data: neuron with N_A antennas
1 **if** SNR *on any antenna is above the limit* SNR_{min} **then**
2   **if** *neuron did not have message from this source yet* **then**
3   select antenna with highest SNR
4   save pair of source and antenna index
5   **end**
6   **if** *neuron had received messages previously from destination of current message* **then**
7   transmit message on saved antenna only
8   **else**
9   transmit message on all antennas
10   **end**
11 **end**

The neuron that receives, for the first time, the message from a specific source relays this message using all antennas. This means that, at the initial phase, the network nodes broadcast all messages and, by doing that, they train themselves. Once trained, the neuron can utilize the distributed antenna system for a more precise message delivery directly towards the destination. Please note that the ultimate goal of the network is ensure that its functionality is realized with minimized energy consumption.

3.3. Wireless Microglia

Wireless microglia nodes, in this case, are the devices very similar to the wireless neurons, for example, they are also equipped with distributed antenna system, but they deliver other functions to the network. In particular, microglia nodes observe surroundings, and if some changes in message flow are detected, like neuron failure (neuron not responding), microglia nodes can enable inbuilt neuron func-

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Algorithm 2: Algorithm of enabling neuron functionality in microglia nodes

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   Data: microglia node with N_A antennas
1 **if** *received a message* **then**
2   save source and destination of the message
3   observe SNR on any antenna
4   **if** *current* SNR *is drastically different from previous saved* SNR *values* **then**
5   enable neuronal functions
6   neurons in range of this microglia node have to start learning from beginning
7   **end**
8 **end**

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tionality, which was inactive so far in order to reduce energy consumption, and transmit data.

In our case, each microglia node calculates the power (and in consequence estimated SNR) of each received message, and if the SNR value observed differs dramatically from previous values (or is even at the noise level), the microglia node switches into active mode. Microglia nodes represent some emergency devices, so if they are enabled, they do not learn the routes of messages and simply transmit the messages using all antennas. The detailed procedure based on which microglia nodes operate is presented in Algorithm 2. In what follows, we denote each of X microglia nodes as Mi, $i = 1, 2, \ldots, X$.

4. Simulation Results

4.1. Simulation Setup

In order to evaluate the performance of the algorithm proposed in the considered scenario, we considered a dense network with 18 wireless neurons at random positions, with their main role being to transfer messages between users. In this case, three network users have been randomly deployed on the borders of the analyzed area, and they exchange messages between themselves. The transmission power of the users was set to 1 dBm and they have only one antenna. The AWGN channel and free space path loss have been considered only. All simulations were performed using the Matlab environment. The distances between the neurons' processing units and the antennas are approximately 1 km, and the distances between neurons equal at least 1.5 km.

Algorithm 3: Main simulation loop

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1 Deploy all neurons, microglia nodes and users
2 **for** Y times **do**
3   generate message from random user *tx* to random user *rx*
4   **while** *user rx does not receive message* **do**
5   **foreach** *node, which has message and did not send it yet* **do**
6   select transmission antenna, based on own saved history
7   **foreach** *node i* **do**
8   calculate SNR
9   **if** $SNR > SNR_{min}$ **then**
10   **if** *node i is neuron* **then**
11   run Algorithm 1
12   **end**
13   **if** *node i is microglia node* **then**
14   run Algorithm 2
15   **end**
16   **end**
17   **end**
18   **end**
19   **end**
20 **end**

We assume the frequency of 3.5 GHz and the system bandwidth of 5 MHz. SNR_{min} was set at 5 dB.

The main simulation procedure is presented as Algorithm 3. The node represents any type of device: a user, a neuron or a microglia node. Note that the results of depend highly on the topology of the network.

4.2. Routing

Let us now observe the routing mechanism implemented in the network due to the application of two algorithms: for neuron learning (i.e. Algorithm 1) and for activation of the neural functions in the microglia node (Algorithm 2). At the beginning, when neurons do not have any knowledge about users' locations, messages simply flood the network. Later, once the learning phase is finished, we can observe the paths created to deliver messages between users.

Let us now analyze the following example of message routing from user 2 to user 1, as shown in Fig. 3. Green points mark the nodes that have already received the message, and red lines mark antennas of the specific nodes that are used to relay data to subsequent neurons. It needs to be noticed that the simulation shows that identification of a specific path between two users results in a significant reduction in power consumption, equaling approximately 85% (compared to the unlearned network).
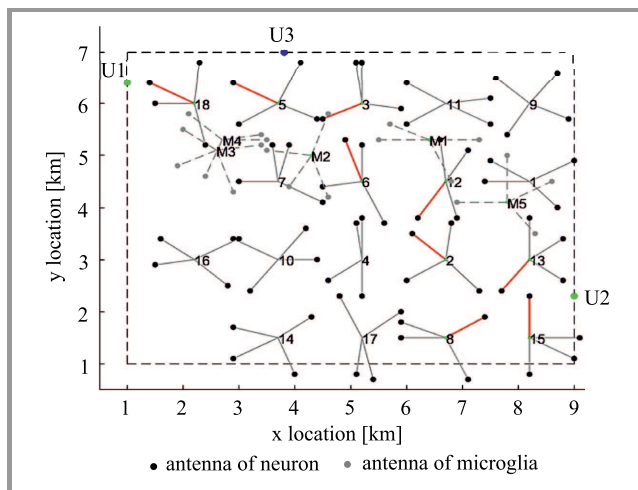

Fig. 3. Route of message from user 2 to user 1 after neuron learning.

After observing the failure of neuron n_6, the microglia node M5 activates its neuronal functionality. It is worth noting that in this example the microglia node M5 is activated and microglia nodes M1 and M2 are not, even though the latter are closer to the faulty neuron n_6. In the algorithm we did not consider direct communication between microglia nodes, so the first microglia node which identifies the problem is turned on. In the considered example, when message from user 2 is sent by neurons n_2 and n_{12}, it is also received by the microglia node M5. Then microglia node M5 waits for the confirmation message (as in saved history) sent by neuron n_6, but does not received anything (due to neuron

failure), so it turns on its own neural functionality. Another reason for not activating the nearest microglia nodes stems directly from our algorithm. A microglia node must first receive a message to have the ability of resending it in the case of an emergency. In this specific coincidence, microglia nodes M1 and M2 do not receive any messages after the failure of neuron n_6. The new path for transferring the message transfer from user 2 to user 1 is shown in Fig. 4. It is important to point out that the path between users 1 and 3 did not change. Let us note that neurons n_1, n_9 and n_{11} could potentially transmit using one antenna, but after erasing their memory (due to the fact that the neuronal functionality of the microglia node is enabled) they will not receive any new messages from user 1. This means that this neuron does not know where the destination user of the message is. In order to solve this, periodic update messages from all users may be broadcast. More precisely, at some particular time stamps, each neuron will send a message using all antennas. This will result in an update of the network topology in every neuron.
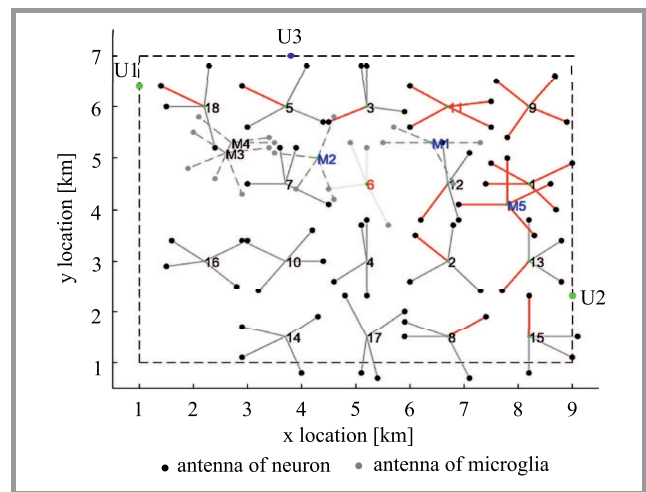

Fig. 4. Route of message from user 2 to user 1 after neuron learning and after neuron n_6 being damaged.
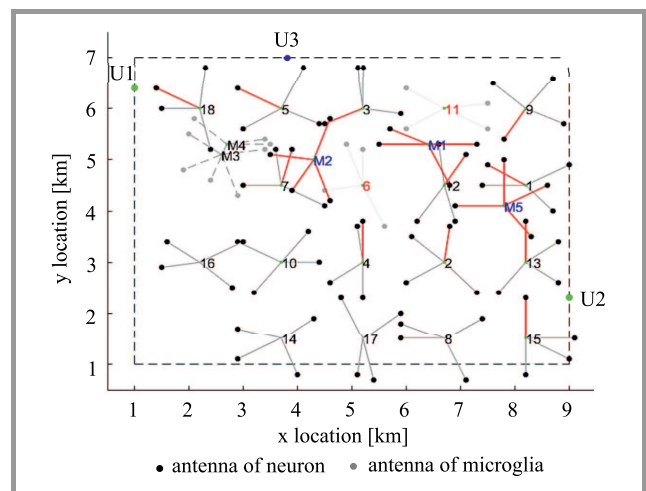

Fig. 5. Route of message from user 2 to user 1 after neuron learning and after neurons n_6 and n_{11} being damaged.

Let us now consider another failure that has happened in this network. After the failure of neuron n_{11} is detected, microglia nodes M1 and M2 activate their neuronal functionality. The new resultant path is shown in Fig. 5.

4.3. Network Fault Tolerance

To evaluate performance of the considered solution, we have analyzed the tolerance of the network to neuron faults. As in the previous subsection, the network topology (as shown in Fig. 1) comprises neurons n_6 and n_{11} (marked red) which stop working properly at one-third and two-thirds of the simulation period, respectively. These time stamps correspond to approx. 12 and 24 messages sent. The blue color of microglia nodes M1, M2 and M5 indicates those microglia nodes which enabled the transmission due to failure detection. In Fig. 6 energy consumption (by the radio portion) and the number of message hops in the network along the path between user 2 and 1 are presented. It may be noticed that energy consumption in the network is very high at the beginning, when neurons do not know where the users are located. The lowest energy consumption value

Fig. 6. Power consumption and number of hops on route of message from user 2 to user 1.

Fig. 7. Power consumption and number of hops on route of message from user 3 to user 1

is observed when network learning is completed and every device works properly. When neuron n6 stops working, the microglia node M5 turns on its neuronal functionality and the message still reaches its destination, but with higher energy consumption and with more hops. Without microglia nodes and in the presence of the same failure, messages from user 2 cannot reach their destination. On the other hand, it may be noticed that there is no difference in message flow between users 3 and 1, even when neurons n_6 and n_{11} stop working.

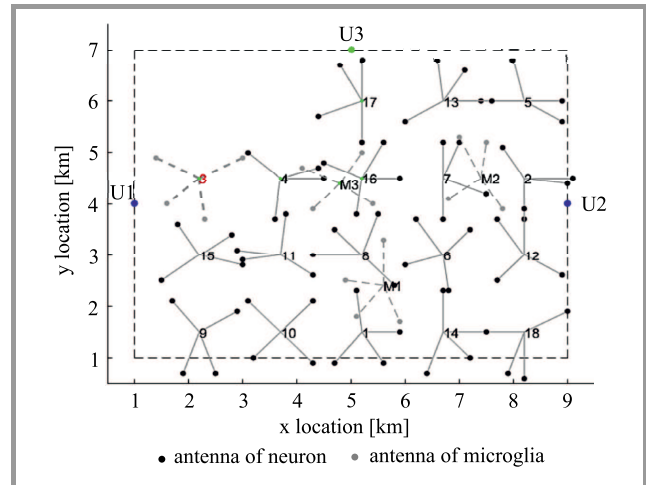● antenna of neuron   ● antenna of microglia

Fig. 8. Network topology (second scenario).

It is important to notice that the proposed algorithms substantially depends on network topology. To evaluate the potential problems and challenges, two other examples are analyzed. In Fig. 8 we can see that once the failure of neuron n_3 has occurred, the distance to the closest microglia node is too high. That is why no microglia node will activate its neuron functionality after the failure of this particular neuron. In consequence, user 1 is unable to communicate with other users. This situation shows that fault tolerance of the network depends highly on the location of microglia nodes. One possible solution to this problem assumes the deployment of microglia nodes closely to each neuron. This will offer a significant increase in fault tolerance, but a high additional hardware cost is required and a resultant increase in energy consumption is observed.

In the third scenario, illustrated in Fig. 9, 18 neurons and 10 microglia nodes have been deployed. Thus, we should achieve a better protection of neurons than in the previous scenario. In that case, once the failure of neuron n_{16} has occurred, we can observe activation of subsequent microglia nodes, resembling the flooding effect. The failure of this neuron has caused 8 microglia nodes activations, because each of the microglia nodes along the route of the message has observed some changes in the transmission, and has turned on their neural functionality. The distant microglia nodes (M6 and M10) are simply too far away from the message route, so they fail to observe the changes concerned. This behavior results in the network connections being repaired, enabling the messages to be once again exchanged
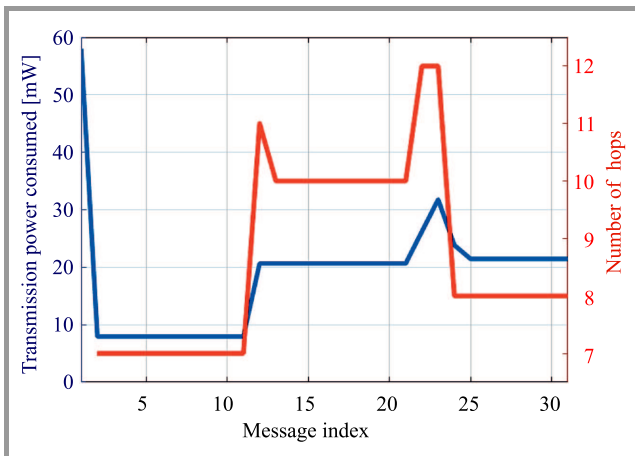
Fig. 9. Network topology (third scenario).

between users. However, in terms of energy efficiency, this is not the best solution. In order to cope with this problem, one option is to suspend the activation of other microglia nodes when the first (closest) one has already been activated (no flooding effect will be observed). This may be realized by the introduction of a dedicated *pause* message which is sent by the *just-activated* microglia nodes, through a dedicated channel, to all nearby microglia nodes, or as a control message. With that change, the failure of neuron n_{16} activates the transmission ability only in microglia node M3, and prevents other microglia nodes from activation. Let us now compare the transmit power consumption (i.e. with and without the *pause* message), and the number of hops in both scenarios, as shown in Fig. 10.

Fig. 10. Power consumption and number of hops on route of message form user 2 to user 1.

It can be seen that the number of hops changes only for a moment (shortly after failure), but in fails to change in the long-term, in both cases. However, energy consumption is much better in the scenario with the *pause* message. This shows the impact of microglia node redundancy in the network.

5. Future Work

5.1. Control Channel

Analysis of the simulation results leads to the conclusion that, conceptually, activation of other microglia nodes should be suspended once the right microglia node had turned on its neural functionality. Each activation of microglia nodes in the aftermath of a neuron failure changes the route along which the message passes between the users. From the point of view of other microglia nodes, such a change may be observed as a neuron failure, which is incorrect. There are two methods that seem to be worth considering in future research. First, a dedicated control channel between the microglia nodes may created, where various control messages (such "suspend activation for a specific period of time") could be transmitted. In such a case, control and data channels occupy various frequency bands. In the second approach, an in-band transmission of control type messages is envisaged, where control messages are mixed with user data on the same physical channel.

5.2. Multiple Activation

Another issue is related to the fact that in our experiment each microglia node activation is associated with dropping the routing memory of nearby neurons, but it can be currently activated only once, and another activation of an already activated microglia node is impossible. By assumption, the microglia node was set as a single use repair device, exactly like a microglia in the human body, where cells of this type are used as the first line defense deployed by the immune system. However, in practice, a dedicated mechanism reverting the microglia node to an idle state or enabling its multiple activations is necessary, and should be the object of future work.

5.3. Switch between Simplified and Advanced Data Transmission

In the considered scenario, very short distances between nodes in the network are considered, and, in consequence, the wireless link may be analyzed as one that is dominated by the additive white Gaussian noise with a dominant direct line of sight. In such a case, one may consider the relaxing of any advanced signal processing technologies (including coding). In specific cases, even a distinct type of an analog transmission could be considered to minimize, to the extent possible, the energy consumed by the node for signal processing and for removing the quantization noise. In this case, we can benefit from lower energy consumption due to a simpler transmitter and receiver structure. Therefore, in our opinion, it would be interesting to evaluate a mechanism for selection of when and where in the network advanced signal processing schemes could be switched off, leaving space for a fully simplified, analog-like transmission.
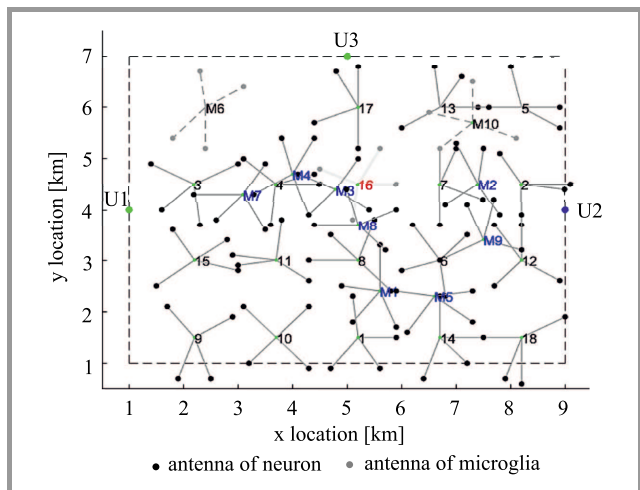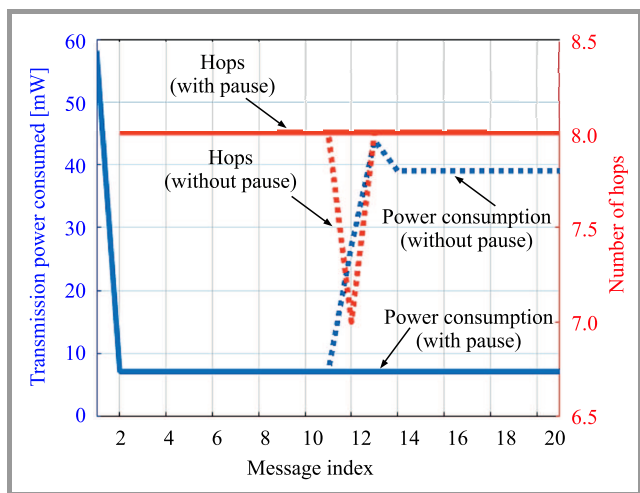
6. Conclusion

The simulation shows that the human brain and nervous system is a big source of inspiration for current and upcoming communication systems. The functionality observed seems to be useful and may be applied, in certain cases, in wireless networks as well. Wireless neurons in our system are stand-alone devices which do not require a central management unit, which provides scalability and easy reconfiguration for a dense wireless network. Moreover, the functionality of microglia nodes may be applied in order to increase the level of fault-tolerance of the system. The simulations conducted proved the correctness of our approach, showing that the application of additional, human brain-inspired solutions may lead to an increase in network performance. For example, we foresee that addition of the myelin sheath functionality may be a topic of future research. In order to reduce the transmission delay, neurons with myelin sheath could transmit with a higher power to reduce the number of hops within the network.

Acknowledgments

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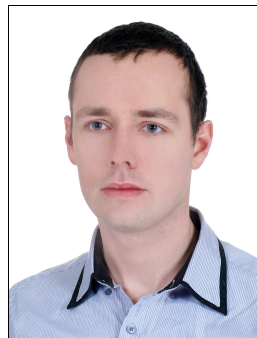
Łukasz Kułacz received his M.Sc. degree in Telecommunications from the Poznan University of Technology, Poland, in 2018, where he is currently pursuing the Ph.D. degree with the Chair of Wireless Communications, PUT. His main fields of interest include programming, wireless communications and algorithm design.

https://orcid.org/0000-0002-3434-1917
E-mail: lukasz.kulacz@put.poznan.pl
Faculty of Electronics and Telecommunications
Poznan University of Technology
5, M. Skłodowska-Curie Sq.
60-965 Poznań

Adrian Kliks received his M.Sc. and Ph.D. degrees in Telecommunications from the Poznan University of Technology, in 2005 and 2011, respectively. Since 2011, he has been an Assistant Professor at the Chair of Wireless Communications. His research interests cover a wide spectrum of wireless communications, in particular new waveforms for future wireless systems, including orthogonal, non-orthogonal and non-contiguous multicarrier schemes. He is also interested in the application of cognitive radio technology, advanced spectrum management, deployment and resource management in small-cells, as well as network virtualization.

https://orcid.org/0000-0001-6766-7836
E-mail: adrian.kliks@put.poznan.pl
Faculty of Electronics and Telecommunications
Poznan University of Technology
5, M. Skłodowska-Curie Sq.
60-965 Poznań