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Method of limiting the emissivity of WSN networks

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Abstract: Wireless sensor networks (WSNs) are a current topic of research that find usage in many applications from environmental monitoring and health protection to military applications. In this paper, analysis of the possibility of reducing the emissivity of radio sensor networks with the assumed transmission probability is discussed. This has a direct influence on power consumption by the nodes and network lifetime. A method based on introducing retransmissions on individual links creating paths between the nodes is presented. Two approaches are used in analyses, the first one being deterministic methods and the second one simulation. Both methods are used to determine the emissivity of the network. The obtained results are compared with a method that uses retransmission on entire paths. This shows that emissivity is more than five times less than the values obtained by retransmission on entire paths.

Key words: Network emissivity, probability of correct transmission, reducing the emissivity

1. Introduction

Wireless transmission technologies are beginning to play an increasingly important role in our daily lives due to their low costs and the ability to quickly deploy into operation. This is possible because of the increasing capabilities of the IT equipment being developed, the progressive miniaturization of electronic systems, and the development of specialized software and information transmission techniques.

One of the technologies used for data transmission is the wireless sensor network (WSN) [1, 2]. These are wireless low-power transmission networks with very low power consumption, implemented on the latest solutions of monolithic radio transmitting and receiving systems, whose nodes directly cooperate with sensors of different measurable parameters. These networks are created by distributed, independent modules that communicate with each other via electromagnetic waves. WSNs are used to perform specific tasks. For example, they can measure temperature, pressure, or the degree of air pollution. They are used in supervision of agricultural crops [3, 4]; dispersed industrial installations, where access to measured parameters is difficult or even impossible for service [5]; patient health monitoring systems [6]; intelligent building systems, for monitoring the condition of infrastructure elements [7–9]; military applications on the battlefield [10]; and automatic meter reading systems [11], to name a few. As already mentioned, these systems are created by nodes that are responsible for data collection, preprocessing and relaying data to neighboring nodes. Radio transmitted data are forwarded to the acquisition node, where they are collected and subjected to further processing and analysis.

The main disadvantage of this type of technology is its vulnerability to external interference, and because of the function it performs, it must ensure an adequate level of transmission reliability. This level depends on

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the network configuration, distance between nodes, static (terrain) obstacles, and motility (disturbances caused by moving objects, etc.). To some extent, the problem of increasing reliability can be solved by increasing the signal level of transmitters, which in turn increases the energy consumption from the power source of the transceiver. The consequence of this phenomenon is the limitation of the operation time of individual nodes, and thus also the entire network.

The unique characteristics of WSNs pose several challenges in their design. These include limited battery capacity, limited hardware and resources, massive and random deployment, and dynamically changing and unreliable environments. The rapidly growing number of installed low-power radio devices, which are the source of electromagnetic radiation, causes the increase in the significance of the issue of reducing the emissivity of WSNs. Network emissivity here is the total energy emitted by a network during its functioning over a specified time. The lowering of the value of this parameter is possible with its correct setup and by using new or modifying already used protocols [12–16]. This aspect has become the basis for the interest in the issues regarding the reducing of the radiation generated by last mile radio and telemetric wireless networks [17–19].

In this paper, the authors present an analysis of the possibility of reducing the emissivity of radio sensor networks, with the assumed transmission probability. The presented analysis compares the effect of the retransmission mechanism described in detail in [17], which was based on the retransmission implemented for the whole routing path.

The paper is structured as follows: Section 2 describes related works, Section 3 describes the proposed solution of the network emitting issue at a set level of probability of correct transmission, Section 4 discusses the determination of the volume of emitted energy using retransmission on different links creating a path, and finally the results obtained and the conclusions drawn from the work are presented in Section 5.

2. Related works

In order to select the optimal topology for the network, the following factors should be taken into account [20]: cost of network implementation (connection costs) expressed as total number of used links; delay of data transmission (communication delay), which is a measure of the size of the diameter (diameter) and the average path length (average distance); fault tolerance, which is characterized by the number of independent paths between two nodes (connectivity) or the minimum number of nodes or links after which the network is no longer consistent (node edge connectivity); regularity and symmetry; simplicity of routing (ease of routing); and scalability (extensibility). Many scientific centers use graphs to analyze various network topologies [21–25]. The research usually focuses on searching for such topologies that will guarantee minimum values of diameter and average path length with acceptable investment expenditures [26, 27].

As seen from the available publications, network capacity and delay data transmission are strictly correlated with the size of the diameter [28, 29] and the average path length [30]. The smaller these values are, the higher the bandwidth of the network and the lower the network delay. The diameter value gives a view of the maximum delay of the transmitted data, which will be the sum of delays arising in intermediate nodes. This delay comes from the routing function performed by the nodes [31]. The delay consists of the time needed to analyze the header, packet buffering, and in the case of optical fiber networks, time to convert optical signals into electrical signals. The size of the average delay of transmitted data is closely related to the average length of the path characteristic for a given structure. If it is smaller, the data sent earlier will reach the destination, which results in less network resource utilization. This allows to share these resources with more users or to increase the real bandwidth between nodes.

An interesting direction of research and analysis is the use of the network optimization method utilizing connection generators [32, 33]. This work focuses primarily on the development of algorithms to support the design and optimization of network parameters. Two types of approaches to solving this problem can be distinguished. In the first case, special programs are used for a predetermined topology with a specified number of nodes. These programs generate additional connections in a deterministic or pseudorandom way and control the diameter and average length of the path in each step of the iteration, so as to allow selection of the optimal network. The second method is based on the elimination of existing connections in a full graph, a "mesh" structure, or some other topology. This allows for obtaining the least complex (cheapest) topology that guarantees the assumed values of the parameters mentioned above or the assumed reliability [28, 34].

Currently, little attention is paid to the phenomenon of emissivity. So far, the focus is primarily on reducing the power consumed by the node in relation to the power source, which is the battery. However, not all applications in WSN nodes have limited access to energy resources. For these devices, it is not necessary to use sophisticated algorithms that take into account the energy consumption of the node. Theoretically, nodes can work at maximum transmit power while using energy-greedy routing protocols. Unfortunately, access to an unlimited source of energy creates other problems despite the fact that it eliminates the problem of power supply. Working at maximum transmit power generates interference in the transmission medium. This involves transmission errors due to interference in the network. Each radio device is classified as a so-called artificial source of electromagnetic radiation. This means that the emitted radio waves can have direct or indirect effects on living organisms. In the era of ever-growing numbers of small-power radio devices, the issue of emissivity in the networks created by these devices becomes more and more important.

3. Materials and methods

3.1. Reduction of network emitting issues at a set level of probability of correct transmission

The work in [18] presented the concept of reducing the emissivity of radio sensor networks by introducing retransmission with the assumed transmission probability. This method works on the following principle: the source node (called the acquisition node) sends a message addressed to the selected destination node. Knowing the configuration of the network and the number of intermediary links creating individual paths, this node, for a specific time interval, waits for feedback. If it does not receive any, it sends the same message again. This operation is continued until the correct answer is received or until the predefined time limit is exceeded, after which the target node is considered to be inoperative or unavailable.

In this case the retransmission increases the probability of achieving the correct result transmission P_i in accordance with the following rule [35]:

$$P_i = 1 - (1 - p_i)^k, \tag{1}$$

where p_i is the probability of the correct transmission for the entire path connecting the acquisition node to the target node and k is the number of retransmissions.

It was found that the introduction of retransmission reduces the emitted and therefore also the consumed energy from the power source, while increasing the time of data collection in relation to the activities consisting only of raising transmission levels.

In the present work, we will discuss the way to reduce the emissivity of wireless networks by introducing retransmissions on individual links creating paths between the nodes. The adopted principle of operation is as follows. The source node sends the packet and listens if the node to which it has been sent will send it to the next node. If it does not hear the transmission signal, it sends the packet again, and the packet will be supplemented with an indicator that it is a replica of the previously sent message. If in this case it does not find a positive reaction of the addressed node, it will make subsequent retransmissions, which will be repeated until it is determined that the packet has been sent to the next node or to exceed the assumed maximum number of repetitions specified for the given connection. It is assumed that each packet has a TTL field (time to live) decremented after reaching the next node or after retransmission, in order to limit the possibility of endless packet switching in the network. If the transmitting node does not pick up a signal from the node to which it was transmitted, and the node has forwarded the information, the next message will be ignored by this node, due to its indicator showing the retransmission. If the acquisition node does not receive feedback within the specified period of time, it recognizes that the connection to the selected node cannot be completed and sends a query message to the next node.

3.2. Principle adopted for determining the probability

The principle of determining the probability of obtaining a correct transmission using the analyzed method will be discussed, which will be illustrated by examples.

Consider the link connecting nodes N_i and N_{i+1} belonging to the jth path connecting any two nodes (Figure 1).

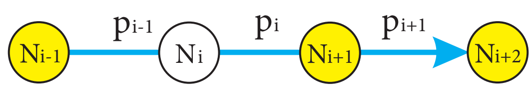


Figure 1. Scheme of the analyzed network.

For the source node to receive feedback from the destination node, the packet must travel a path consisting of $2l$ edges (l denotes the length of the jth path in one transmission direction). The probability of performing a fault-free transmission P_{wj0} is determined by the following formula:

$$P_{wj0} = \prod_{i=1}^{2l} p_i, \tag{2}$$

where p_i is the value of the probability of correct transmission via the ith edge that is part of the jth path.

In order to increase the certainty of correctly sending information via the ith edge, it can retransmit the packet (Figure 2a), which will increase the probability of success by the p_{it1} value:

$$p_{it1} = p_i q_i, \tag{3}$$

where q_i is the probability of failure equal to $(1 - p_i)$.

In this case, the acquisition node should receive feedback after $2l + 2$ time intervals necessary to send information between nodes. It results from the fact that node N_i has to wait the time necessary for node N_{i+1} to receive and send a message to another node. If node N_i does not pick up that N_{i+1} has not forwarded the data further, then it sends a replica of the information.

If the transmission is repeated twice (Figure 2b), then the probability increase p_{it2} will be expressed by the following formula:

$$p_{it2} = p_i q_i^2. \tag{4}$$

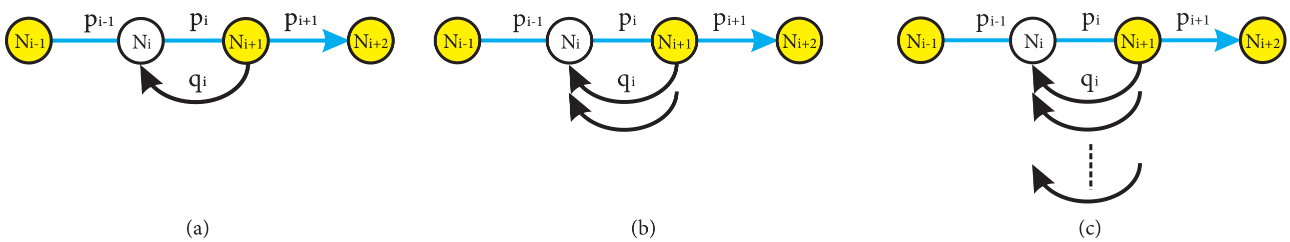


Figure 2. a- One data retransmission via the ith edge, b- two retransmissions; c- greater number of retransmissions.

In general, the probability increments in the function of the number of retransmissions (Figure 2c) can be described by the following relationship:

$$p_{itr} = p_i q_i^r, \tag{5}$$

where r means the number of retransmissions on the given link.

Total probability P_{ir} for the ith edge, which is a part of the chosen path, depending on the number of retransmissions, is determined by the following formula:

$$P_{ir} = \sum_{r=0}^{n} p_{itr} = 1 - q_i^{r+1}, \tag{6}$$

where $r \in \{0, 1, \ldots, n\}$ represents the number of retransmissions on a given link.

By entering them for formula (6), the calculated values for each of the edges included in the jth trace of the path by the resulting probability P_{wj} of the transmission through this path are determined:

$$P_{wj} = \prod_{i=1}^{2l} P_{ir}. \tag{7}$$

To illustrate the procedure, a simple example is used for the explanation. There is a path connecting two nodes created by edges AB and BA. It is assumed that the probabilities of obtaining a correct transmission in both directions are not the same and P_{AB} is equal to 0.70 and P_{BA} = 0.75, while the resultant probability of obtaining a correct feedback should not be less than 0.95.

Table 1 makes it possible to determine the minimum number of retransmissions at transmission levels equal to 0 dBm so as to meet the assumed condition $P_{wj} > P_z$.

Table 1. Auxiliary table.

	P_{AB}	0.700	0.910	0.973	0.992	
P_{BA}	r	0	1	2	3	
0.750	0	0.525	0.683	0.730	0.744	Link BA
0.938	1	0.656	0.853	0.912	0.930	
0.984	2	0.689	0.896	0.958	0.976	
0.996	3	0.697	0.906	0.969	0.988	

Link AB

As Table 1 shows, the assumed resultant probability can be obtained if the total number of retransmissions is 4, 5, or 6.

The calculation of the radiated energy values at the assumed probability level Pz of obtaining the correct transmission of E_{AB} and E_{BA} was made using the following formula:

$$\begin{aligned} E_{AB}[\text{mWs}] &= (r_{AB}+1)\cdot L_n \cdot l_q \cdot t_b, \\ E_{BA}[\text{mWs}] &= (r_{BA}+1)\cdot L_n \cdot l_a \cdot t_b, \end{aligned} \tag{8}$$

where r_i is the number of retransmissions necessary to achieve the assumed probability, l is the number of edges in the path connecting the source node to the destination node, L_n is the power level of the transmission signal [mW], t_b is the duration of one byte or 1 [ms], $l_q = 20$ is the number of bytes transferred from the acquisition node to the destination node, and $l_a = 100$ is the number of bytes sent to the acquisition node [36]. The time of data acquisition was calculated using the following formula:

$$\begin{aligned} T_{AB}[\text{s}] &= (2r_{AB}+1)\cdot l_q \cdot t_b, \\ T_{BA}[\text{s}] &= (2r_{BA}+1)\cdot l_a \cdot t_b. \end{aligned} \tag{9}$$

Referring to the example under consideration, if the transmit level is 0 dBm, the calculated total values of the emitted energy and time of data acquisition are given in Table 2.

Table 2. Designated network parameters.

Number of retransmissions	$r_{AB}=2$ $r_{BA}=2$	$r_{AB}=2$ $r_{BA}=3$	$r_{AB}=3$ $r_{BA}=2$	$r_{AB}=3$ $r_{BA}=3$
E_{ABA}[mWs]	0.36	0.38	0.46	0.48
T_{ABA}[s]	0.60	0.64	0.80	0.84

Thus, it can be concluded that the distribution of the number of retransmissions affects both the amount of energy emitted and the time of data collection.

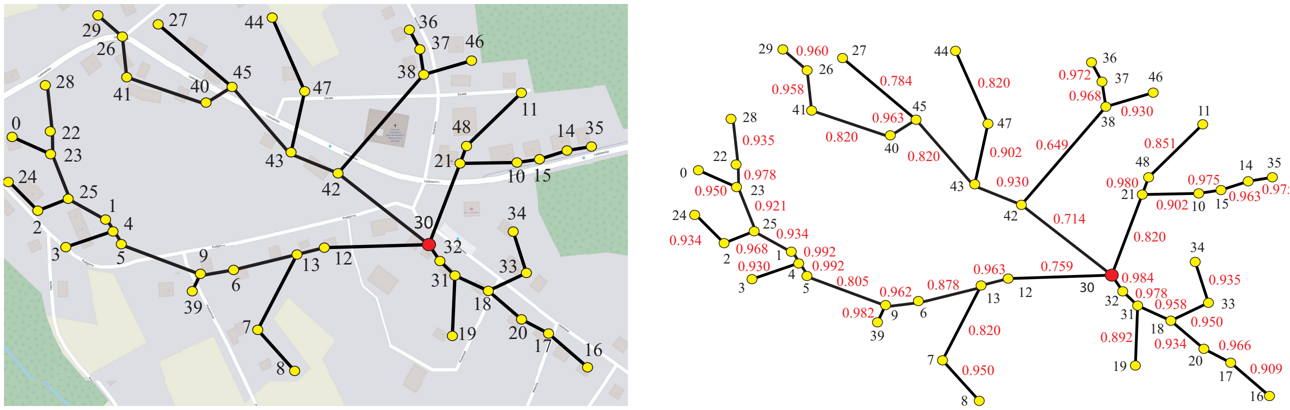
4. Results and discussion

4.1. Determination of the volume of emitted energy using retransmission on different links creating a path

The aim of the work was to check whether and how much the WSN's emissivity can be reduced due to the application of a retransmission mechanism on individual links in relation to retransmissions used on entire paths. Referring to this, the WSN located in the town of Grodek (Kuyavian-Pomeranian Voivodeship) was analyzed (Figures 3a and 3b).

The map showing the topology of this network was downloaded from the OpenStreetMap portal. The analyzed network consists of 49 nodes. Using a developed program [17], it was found that the best location for the acquisition node under these conditions is node number 30 (red marker). The determination of the location of this node was carried out at the transmission level of 0 dBm. Using the aforementioned application, the distances between the nodes shown in the drawing were determined. Next, using the data contained in articles [36, 37], the theoretical values of signal attenuation in free space FSL (free space loss) were calculated:

$$\text{FSL} = 32.44[\text{dBm}] + 20\log(f) + 20\log(d) + 40[\text{dBm}], \tag{10}$$



(a) (b)

Figure 3. a- Network scheme in the town of Grodek, b- probabilities of transmitting through the edges forming a graph describing the network.

where f is transmission frequency (for calculations it was assumed that the radio frequency is 433 [MHz]), d is distance between the transmitter and the receiver [km], and the value of 40 dBm results from the assumption of using an omnidirectional antenna.

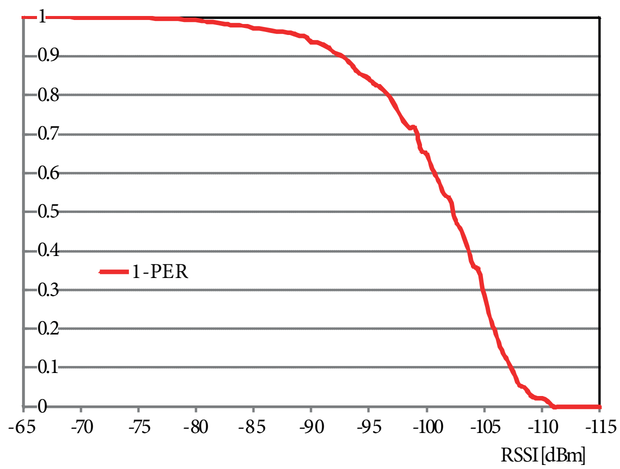


Figure 4. Graph of link quality dependence as a function of the signal level reaching the receiver.

Assuming the same level of radio signal emission and the same sensitivity of receivers, for the calculated level of the signal reaching the receiver RSSI (received signal strength indicator), the PER (packet error rate) parameter values were specified based on the dependence depicted in Figure 4. This was also presented in [36].

Figure 3b shows additionally determined values of the probability transmission for edges (red color) forming individual paths between nodes of the analyzed network.

Table 3 lists the path lengths and calculated values of the probability of performing a faultless transmission, assuming that in both directions the conditions for sending information through each of the links are the same.

With the assumed probability the value of obtaining the correct transmission for each of the paths connecting the acquisition node with the target nodes, the theoretical number of necessary retransmissions was

Table 3. The probability of getting the correct transmission without applying a retransmission.

Node	0	1	2	3	4	5	6	7	8	9	10	11
l_i	10	7	9	6	6	5	3	3	4	4	2	3
P_{wi}	0.160	0.236	0.196	0.210	0.234	0.247	0.412	0.359	0.342	0.382	0.547	0.458
Node	12	13	14	15	16	17	18	19	20	21	22	23
l_i	1	2	4	3	6	5	3	3	4	1	10	9
P_{wi}	0.576	0.535	0.483	0.520	0.573	0.693	0.850	0.738	0.743	0.672	0.170	0.170
Node	24	25	26	27	28	29	31	32	33	34	35	36
l_i	10	8	6	4	11	7	2	1	4	1	5	5
P_{wi}	0.171	0.209	0.170	0.183	0.148	0.156	0.927	0.969	0.768	0.671	0.459	0.392
Node	37	38	39	40	41	42	43	44	45	46	47	48
l_i	4	3	5	4	5	1	2	3	3	3	2	2
P_{wi}	0.415	0.442	0.368	0.275	0.185	0.510	0.441	0.241	0.297	0.434	0.359	0.646

determined. The condition that must be met, the value of the probability of obtaining the correct transmission through each of the edges forming the given path, is defined by the following expression:

$$p_i \geq \sqrt[2l]{P_z}, \tag{11}$$

where P_z is the assumed resultant probability. This condition results from the fact that the probability values are included in the range $(0,1)$, so if the value assigned to any of the edges does not satisfy this relationship, then the product $p_i - p_{\text{ref}}$ will always be smaller than P_z.

By converting expression (11), a formula was obtained allowing to determine the number of retransmissions $r_i = 2l_i$, and for a given edge creating the chosen path it determines the formula:

$$r_i = \left\lceil \frac{\log(p_i)}{\log(p_z)} \right\rceil. \tag{12}$$

To explain the mode of the operation, the values of r_i for the links belonging to the path connecting the 8th node to the 30th node were calculated assuming that $P_z = 0.95$. The path is formed by the edges 8-7, 7-13, 13-12, and 12-30, $l = 4$, so $p_{\text{ref}} = \sqrt[8]{0.95} = 0.9936$.

The calculated values of r_i are given in Table 4.

Table 4. Determining the number of retransmissions.

	Edge			
r_i	8-7	7-13	13-12	12-30
0	0.9510	0.8200	0.9620	0.7590
1	0.9976	0.9676	0.9986	0.9419
2	1.0000	1.0000	1.0000	0.9998
3	1.0000	1.0000	1.0000	1.0000
p_{ref}	0.99361	0.99893	0.99840	0.99680

In this case, the minimum retransmissions are $r_{8-7} = 1$, $r_{7-13} = 2$, $r_{13-12} = 1$, and $r_{12-30} = 2$, while P_w reaches a value of 0.98779.

To ensure that the path length has a significant impact on the number of retransmissions required, Table 5 shows the number of paths that connect the transmitting node with the remaining nodes for the value of $P_z \geq 0.95$.

Table 5. The number of retransmissions necessary to achieve the assumed probability.

Node	0	1	2	3	4	5	6	7	8	9	10	11
r_i	21	14	17	13	12	11	6	7	8	8	4	6
Node	12	13	14	15	16	17	18	19	20	21	22	23
r_i	3	4	7	6	8	6	3	4	5	2	22	19
Node	24	25	26	27	28	29	31	32	33	34	35	36
r_i	19	16	14	12	24	16	2	1	4	3	8	8
Node	37	38	39	40	41	42	43	44	45	46	47	48
r_i	7	6	9	10	13	3	5	10	9	6	7	3

The discussed method of determining the number of retransmissions for a selected path does not allow to assess the distribution of the number of retransmissions in the individual edges making up this path in order to achieve the assumed probability.

For example, the path connecting the 30th node to the 19th node forms edges 30-32, 32-31, and 31-19, for which the probabilities are 0.984, 0.978, and 0.892, respectively. The total number of retransmissions resulting from the calculation is 4. From the analysis it is visible that in order to meet the assumed condition $P_z \geq 0.95$ one retransmission must occur on links 30-32 and 32-31 and two on link 31-19. If all four retransmissions occur, for example, on link 31-19, then the resulting probability for the analyzed path will be 0.926, so $p_i < P_z$.

To eliminate this drawback, simulation tests were carried out [38]. The principle of operation of the program consists in pseudorandom selection of damaged edges of the graph describing the topology of the network and determining the number of retransmissions necessary to meet the assumed condition $p_i < P_z$.

4.2. Calculation and simulation results

Using the above algorithm used in the simulation program, the number of retransmissions r_i necessary to obtain the assumed level of the resulting probability was determined. The obtained results are presented in Table 6.

Table 6. Retransmission numbers resulting from simulation.

Node	0	1	2	3	4	5	6	7	8	9	10	11
r_i	19	14	17	13	13	11	7	7	9	9	4	6
Node	12	13	14	15	16	17	18	19	20	21	22	23
r_i	3	5	8	6	10	9	5	5	7	2	19	17
Node	24	25	26	27	28	29	31	32	33	34	35	36
r_i	18	16	13	10	20	15	3	1	7	2	10	9
Node	37	38	39	40	41	42	43	44	45	46	47	48
r_i	8	6	10	9	11	3	5	8	7	7	5	4

These results were compared with the results of calculations obtained with previously described methods, as shown in Figure 5. As we can see, the chart nature of the number of retransmissions is the same in both methods, which confirms the correct operation of the simulator.

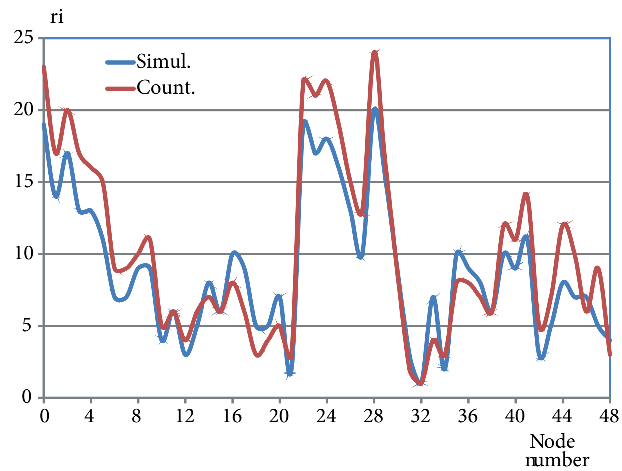


Figure 5. Comparison of the number of retransmissions obtained by the methods used.

Using the following formulas, the values of the radiated energy E_{2l} and the acquisition time T_{2l} were calculated for each path as well as for the whole network:

$$E_{2l}[\text{mWs}] = (r_{ij} + 1) \cdot L_n \cdot l_q \cdot t_b + (r_{ji} + 1) \cdot L_n \cdot l_a \cdot t_b = 20 \cdot L_n \cdot t_b \cdot (r_{ij} + 5r_{ji} + 6l), \tag{13}$$

where E_{2l} is the resultant emissivity of the path and r_{ij} is the number of retransmissions from the source node to the destination node, while r_{ji} is that in the reverse direction.

Assuming that the number of retransmissions in both directions is equally probable, formula (13) assumes the following:

$$E_{2l}[\text{mWs}] = 120 \cdot L_n \cdot t_b \cdot (r_{2l} + l), \tag{14}$$

where r_{2l} is the total number of retransmissions in the entire path.

Table 7 presents the results of calculations of net emissivity values for each of the paths connecting the acquisition node to the remaining nodes.

Table 8 gives the data acquisition time calculated from the following formula:

$$T_{2l}[\text{s}] = 2\,(r_l + l) \cdot (l_q + l_a) \cdot t_b = 240 \cdot t_b \cdot (r_l + l). \tag{15}$$

Based on the obtained results, it can be concluded that the received values of the analyzed parameters differ only slightly (Figures 6a and 6b). All results were achieved at the transmission level of 0 dBm.

The total amounts of radiated energy and the time of data collection have been calculated (Table 9).

4.3. Determination of the network's emissivity

Since the aim of the authors of this article was to minimize the emissivity of the network, the impact of selection of transmission levels on this parameter was also investigated. To accomplish this goal, the results obtained by simulations were used. Figure 7 presents the results of the analysis of the function of changes in levels of

Table 7. Results of emissivity calculations.

Node	0	1	2	3	4	5	6	7	8	9	10	11	*Mode*
E_{2l}	4.92	3.36	4.20	3.00	2.88	2.52	1.44	1.56	1.92	1.92	0.96	1.44	*Calcul.*
[mWs]	4.56	3.12	3.84	2.76	2.64	2.4	1.2	1.32	1.8	1.56	0.84	1.2	*Simul.*
Node	12	13	14	15	16	17	18	19	20	21	22	23	*Mode*
E_{2l}	0.60	0.96	1.80	1.44	2.40	1.92	1.08	1.20	1.56	0.48	5.04	4.44	*Calcul.*
[mWs]	0.36	0.84	1.44	1.08	1.8	1.56	0.72	0.84	1.08	0.36	4.44	4.2	*Simul.*
Node	24	25	26	27	28	29	31	32	33	34	35	36	*Mode*
E_{2l}	4.68	3.84	3.12	2.40	5.52	3.60	0.72	0.36	1.44	0.60	2.16	2.16	*Calcul.*
[mWs]	4.08	3.48	3.24	2.16	5.04	3.48	0.48	0.24	1.08	0.36	1.8	2.04	*Simul.*
Node	37	38	39	40	41	42	43	44	45	46	47	48	*Mode*
E_{2l}	1.80	1.44	2.28	2.16	2.76	0.60	1.08	1.92	1.80	1.44	1.32	0.84	*Calcul.*
[mWs]	1.68	1.2	2.04	1.68	2.52	0.48	1.08	1.8	1.44	1.32	1.2	0.72	*Simul.*

Table 8. The results of calculations of acquisition time.

Node	0	1	2	3	4	5	6	7	8	9	10	11	*Mode*
T_{2l}	7.44	5.04	6.24	4.56	4.32	3.84	2.16	2.40	2.88	2.88	1.44	2.16	*Calcul.*
[s]	6.96	5.04	6.24	4.56	4.56	3.84	2.40	2.40	3.12	3.12	1.44	2.16	*Simul.*
Node	12	13	14	15	16	17	18	19	20	21	22	23	*Mode*
T_{2l}	0.96	1.44	2.64	2.16	3.36	2.64	1.44	1.68	2.16	0.72	7.68	6.72	*Calcul.*
[s]	0.69	1.68	2.88	2.16	3.84	3.36	1.92	1.92	2.64	0.72	6.96	6.24	*Simul.*
Node	24	25	26	27	28	29	31	32	33	34	35	36	*Mode*
T_{2l}	6.96	5.76	4.80	3.84	8.40	5.52	0.96	0.48	1.92	0.96	3.12	3.12	*Calcul.*
[s]	6.72	5.76	4.56	3.36	7.44	5.28	1.20	0.48	2.64	0.72	3.60	3.36	*Simul.*
Node	37	38	39	40	41	42	43	44	45	46	47	48	*Mode*
T_{2l}	2.64	2.16	3.36	3.36	4.32	0.96	1.68	3.12	2.88	2.16	2.16	1.20	*Calcul.*
[s]	2.88	2.16	3.60	3.12	3.84	0.96	1.68	2.64	2.40	2.40	1.68	1.44	*Simul.*

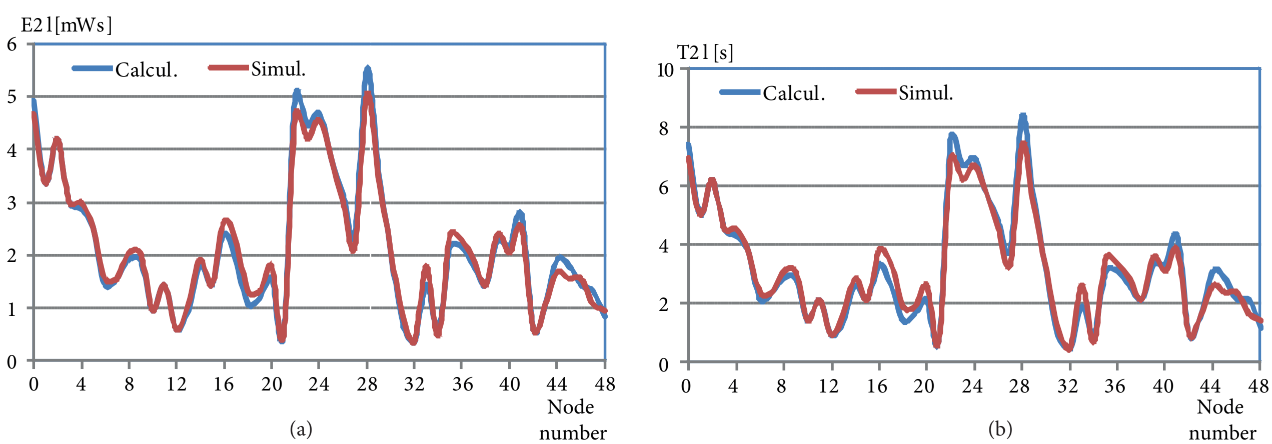


Figure 6. Graphs of a- emitted energy and b- data acquisition time.

Table 9. Comparison of the determined network parameters.

Parameter	Calculation	Simulation
E_w[mWs]	100.68	90.60
T_w[s]	154.80	155.04

information broadcasting (Figure 7a) and shows that a lower level of broadcasting gives a longer acquisition time (Figure 7b).

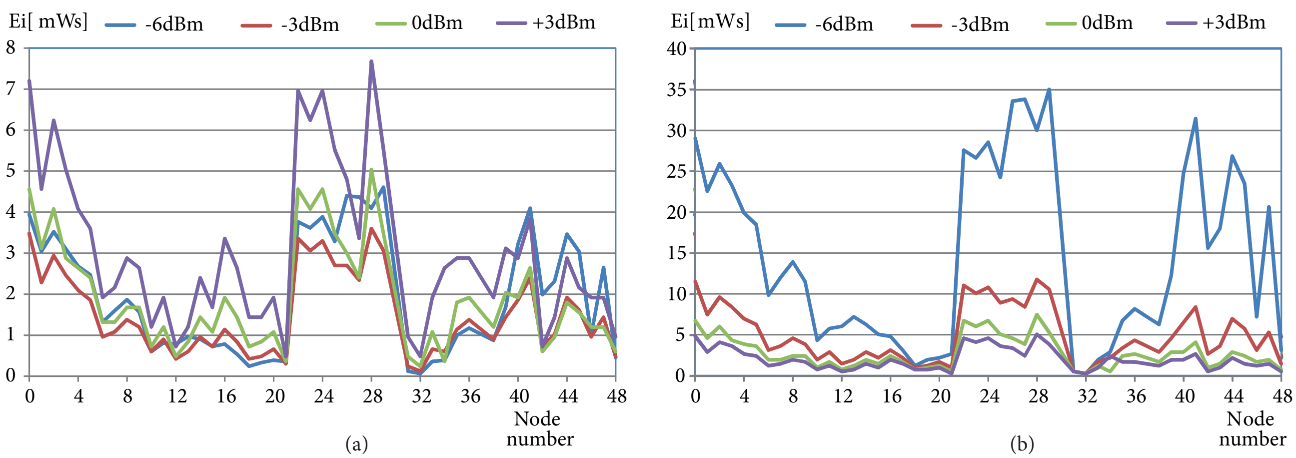


Figure 7. Results of the comparison of network parameters for the function of changes in the transmission level: a- emitted energy; b- acquisition time.

The total values of the analyzed parameters were determined as a function of changes in transmit levels, which are presented in Table 10.

Table 10. Values of the tested parameters in the function of changes in transmission levels.

L [dBm]	–6.0	–4.5	–3.0	–1.5	0.0	1.5	3.0
E_w[mWs]	93.49	73.44	71.88	78.78	91.56	115.39	145.68
T_w[s]	693.60	362.40	236.40	171.36	131.76	112.32	94.32

The obtained data show that the optimal transmission level is included in the range of –4.5 to 3 dBm. For the minimization of radiated energy, it is necessary to select the levels of radio signals through which information will be transmitted (for larger networks, this may be important).

The initial goal of the analysis was to compare the retransmission method discussed above in relation to the method discussed in [17] involving retransmission of data across the entire path. The results obtained are shown in Table 11.

On the basis of the received data, the network's emissivity and the time of data acquisition were calculated using the following formulas:

Table 11. The number of retransmissions calculated for the case of resending the packet through the entire path.

Node	0	1	2	3	4	5	6	7	8	9	10	11
r_i	17	10	13	12	10	10	5	6	7	6	3	4
Node	12	13	14	15	16	17	18	19	20	21	22	23
r_i	3	3	4	4	3	2	1	2	2	2	16	16
Node	24	25	26	27	28	29	31	32	33	34	35	36
r_i	15	12	16	14	18	17	1	0	2	2	4	6
Node	37	38	39	40	41	42	43	44	45	46	47	48
r_i	5	5	6	9	14	4	5	10	8	5	6	2

$$E_w[\text{mWs}] = 120 \cdot L_n \cdot t_b \cdot r_i \cdot 2\,l, \quad (16)$$

$$T_w[\text{s}] = 120 \cdot t_b \cdot r_i \cdot 2\,l. \quad (17)$$

In this case ($L_n = 0$ dBm), the calculated total values of the emitted energy were 496.32 mWs, and acquisition time was 496.32 s, while the values of these parameters obtained by means of the above-mentioned method were respectively 91.56 mWs and 131.76 s. In Figures 8a and 8b, differences in the size of the analyzed parameters for both compared methods are shown.

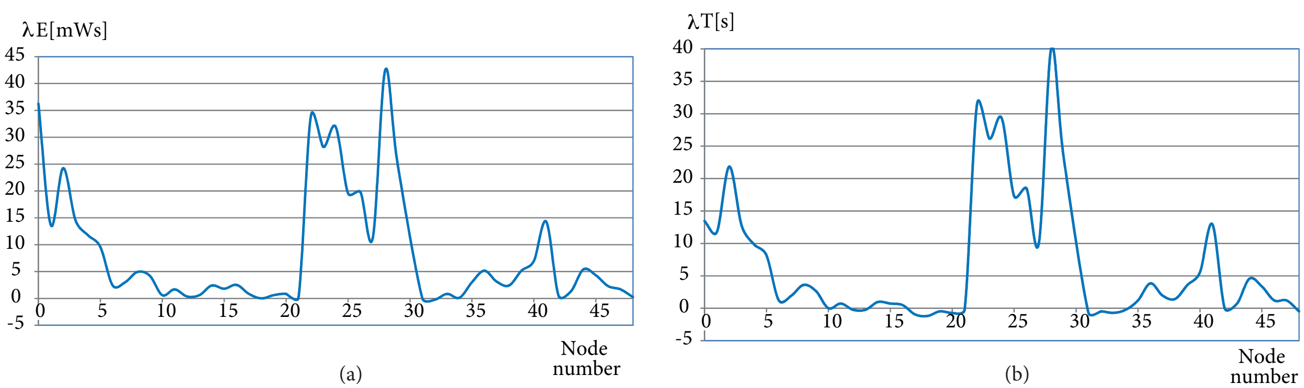


Figure 8. Comparison of results obtained due to retransmission on entire paths and at their individual edges: a- emitted energy; b- acquisition time.

Their total values obtained through the use of the retransmission method at individual edges regarding emissivity are more than five times, and if by time almost four times smaller, than the values obtained by retransmission on entire paths.

5. Summary and conclusions

This article presents an analysis of the possibility of reducing the emissivity of radio sensor networks, with the assumed transmission probability, thanks to the introduction of retransmissions at individual edges forming paths connecting the acquisition node to the target nodes. The principle of determining the probability of obtaining a correct transmission using the above-mentioned method was discussed and illustrated by examples. The deterministic way of specifying the number of retransmissions for paths connecting the acquisition node with the target nodes, fulfilling the assumed condition concerning the probability of obtaining the correct transmission, was described. The simulation program was also used to determine the number of repetitions. The results obtained with both methods were compared, stating that they differ to a small extent. Using the obtained results, the emissivity values and the time of data acquisition for individual paths as well as for the entire network were calculated. These tests and calculations were also carried out by changing emission levels, proving that the choice of their value affects the volume of electromagnetic waves emitted. The obtained values of the analyzed parameters were compared to the same values obtained when using the retransmission principle performed on entire paths. They showed that emissivity is more than five times less than the values obtained by retransmission on entire paths. It can be concluded that they are definitely better, from the point of view of limiting the emissivity of the network, so it is recommended to use retransmissions on individual links.

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