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AN ANALYSIS OF THE APPLICATIBLITY OF "HOT-POTATO" ROUTING IN WIRELESS SENSOR NETWORKS USED IN ENERGY CONSUMPTION MONITORING SYSTEMS

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Summary: The subject of this paper is analysis of possibility of application "Hot--Potato" protocol in the Wireless Sensor Networks (WSN), which can be used to collect, store and process data obtained from the media consumption meters. Authors propose to use this protocol on account of its low energy emission and small memory capacity while ensuring the high reliability. To perform this analysis the elements of graph theory were used.

Keywords: WSN, Hot Potato protocol, graph, spanning tree, adjacent matrix, diameter, average path length

1. INTRODUCTION

Dynamic development in the field of wireless transmission technology has aroused interest in building sensor networks. A wireless sensor network (WSN) consists of many cheap and small-sized energy efficient devices, located over a certain area in order to accomplish a common task [6, 10]. These networks can perform a variety of functions connected with monitoring of different objects, collecting data from recording devices; they can also be used in industry as well as for collecting media consumption data by companies supplying users with electricity, gas or water. In the last case, application of the above mentioned technology enables automatic, remote reading of a medium consumption by a user, which not only reduces employment costs but also provides users with service and comfort (no need to wait for the collector, improvement in the security thanks to elimination of the risk of being intruded by unauthorized persons).

The basic element of a sensor network is a node consisting of a sensor monitoring the medium consumption, including processor with limited computing possibilities and a battery or an external power supply (the node is assumed to take a small amount of energy). Another task, apart from the main one which involves data recording, is to transmit it over the radio path to a given node (acquisition center) and also, if necessary, transmit information coming from/to other nodes.

A typical node of WSN consists of an antenna, a microcontroller, a transmission – reception system and a sensor. Nodes of different networks can vary considerably from each other (it results from a variety of tasks to perform); however it is possible to distinguish some elements they have in common. These elements are: measurement module, calculation module, transmission module, supply module and operational system. The task of the measurement module is to collect information gathered by the node. The measurement results, in a digital form (analogue signal is converted into digital one), are transmitted to the calculation module where they are transformed. The calculation model consists of a microcontroller or microprocessor with memory and plays the most important role in cooperation with microprocessors. The transmission module receives and transmits information between the network nodes. The operational system, being the processor central part, manages and controls all the above mentioned modules, enables data transmission between them and monitors their operation.

Most frequently, one module of the sensor network is distinguished and it constitutes the acquisition center. Its task is collecting, storing and processing information coming from each of the sensors belonging to the network. The node equipment is much more developed and the processor possibilities are significantly better than those of the standard node.

Two main features of sensor networks are: connectivity and coverage [11]. Connectivity means the ability of data transmission between all nodes of the network on the condition that it is being able to provide possibilities to transmit information between adjacent nodes (which results from low radio powers generated by sensors), whereas coverage means capability of gathering information from the assigned area.

While building a sensor network it is necessary to account for factors that have a significant influence on the design process and later on its operation. These include:

- Fault tolerance. Some nodes of a sensor network can be unfit for use due to lack of energy, physical contamination, or environmental impact. However, such a situation should not affect accomplishment of the network basic task.
- Scalability. A sensor network can consist of hundreds or even thousands of sensor nodes. For this reason, applications must be designed in such a way that they will be able to operate with a big and variable amount of nodes.
- Production costs. As it has already been mentioned, sensor networks are most often made up of a large number of nodes, thus the cost of a single node has a big influence on the total cost of the whole enterprise.
- Work environment. Sensor networks can operate in various, sometimes extreme, conditions, therefore, the nodes are required to meet very high standards connected with resistance to interference and disruption by external factors.
- Transmission medium. Most frequently communication between nodes is carried out by means of radio waves, though transmission using infrared radiation or optical medium is applied as well.
- Power consumption. In sensor networks using a wireless medium the power intake is of great importance. Sensor nodes are based on microelectronic subsystems must be equipped with a source of electrical energy of limited power since in many cases there is no possibility of its frequent exchange, therefore, the battery life time largely limits costs and efficiency of the whole network. In multi-hop networks where information is transmitted by many nodes, this is the node which is the information source and receiver, and it performs the function of a router. The node turning off or damaging causes the network topology change and involves the necessity of

introduction of new routings, that is, reorganization of the whole network operation. Energy efficiency and its appropriate management need to be accounted for as soon as in the stage of the network design. Thus, energy efficient solutions for subsystems, protocols and algorithms are being continuously searched for.

Recently, many communication protocols have been elaborated for WSN networks, where the basic assumption for their design is to solve the problem of a long-term node feed [10]. In typical networks, the choice of the route is made in such a way that it is possible to transmit information with possibly smallest total emitted energy with intermediate nodes being uniformly loaded by energy, over the whole time of the network operation. In WSN networks used for building energy consumption monitoring systems, the energy efficiency problem does not appear in most cases. Therefore, in such systems energy inefficient (with high energy consumption), simple routing protocols can be used, e.g. protocols of the type 'Multi-hop by Flooding'.

Acceptance of this kind of solution has two advantages – it provides highly reliable transmission involving possibility of simultaneous transmission of packets through different routes and makes it possible to reduce requirements concerning the capacity of memory installed in the sensor node. The advantage is of special importance as in systems of remote readings it is necessary to have increasingly higher capacity for implementation of more and more complicated coding algorithms. Additionally, the biggest part of memory RAM has to be designed for transmission-reception buffers which are the effect of transmission of packets with increasing length that must be handled by WSN networks.

Despite the advantages there is a certain drawback of protocols of the type 'Multi-hop by Flooding' which, in combination with the assumption of a wider application of the discussed network, limits its use possibilities. This drawback is its high protocol emissivity amounted w - 1 for a network containing w number of nodes.

For this reason, the authors of the paper focus on an analysis of possibilities of using 'Hot-Potato' (HP) protocol. Advantages of this protocol are reflected by its below mentioned features:

- It is a reliable protocol as in the process of choosing neighbors, the node chooses only those adjacent nodes which ensure small probability of information transfer error occurrence;
- Despite redundant number of hops, HP protocol is of low emission character because:
  - It is a connectionless protocol (path does not need to be formed);
  - In a given moment, only one node of the whole network can be in the state of transmission;
  - Alternative routes are not set up (as it is done, e.g. in Multipath–Based Routing).
- It needs relatively small capacity of RAM memory as package buffering is not required, and there is no need to know the whole network topology and memory has only the list of neighbors recorded.
- Packages are transferred fast as during the package transfer, delay time is not required;
- Does not require complicated, fast and highly developed equipment;
- Is of non-collision character.

Routing "Hot-Potato" protocol was described for the first time in 1964 in [2]. It found wide application no sooner than in the second half of the 90s, mostly in fast fiber networks [1, 3, 4, 5, 7, 13, 14] where it is better to transmit a packet by fast links through a bigger number of nodes, than to waste time for their buffering, until the optimal route becomes available. For this reason, this protocol is frequently called a deflective protocol. In the solution the node does not know the optimal route, therefore there cannot by any deflection from the optimal route, it is why it is preferred to call this protocol "Hot-Potato" instead deflective protocol. The authors of this paper have not found many publications on the subject of "Hot-Potato" protocol application in systems of wireless communication, and it appears that in WSN networks with relatively fast links (from several to several hundred kb/s) and nodes with poor memory, this protocol can successfully be used.

The subject of this article is an analysis of applicability of elements of graph theory for the design of sensor networks based on "Hot-Potato" protocol. The main contribution of the paper is the demonstration of probability of packet delivery. First a theoretical analysis is presented, based on graph theoretical concepts, and applied to a concrete example. Next the theoretical analysis is confirmed through simulations.

2. PURPOSE OF THE ANALYSIS AND METHODS

The subject of the presented analysis is a specific sensor network designed for a remote reading of media consumption by individual users. This kind of network, as any other one, can be described by means of a graph. Each graph, in turn, can be described by their adjacency matrix [***AM***] [8], that is a matrix which defines mutual incidence of the graph nodes [12]. This matrix is a square one of w x w dimension (where w denotes the number of nodes forming this network) with elements am_{ij} which assume values from set {0, 1}, whereas:

– $am_{ij} = 1$, when there exists an edge connecting nodes w_i and w_j .
– $am_{ij} = 0$, when there no exists an edge connecting nodes w_i and w_j.

To illustrate the presented considerations, a simple example of a network shown in fig. 1, has been used.

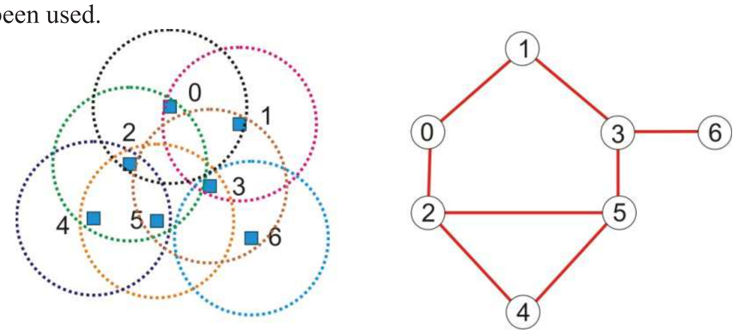


Fig.1. An example scheme of a sensor network and a graph describing it – circles define the range of radio transmission.

The analyzed network consists of 7 nodes and is described by the following adjacency matrix:

$$[AM] = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

The exponentiation of adjacency matrix allows to calculate the number of routes with length ***l*** which connect two random vertices of the graph (a route is an alternate series of nodes and edges in which each node and each edge can appear many times and the number of edges forming a given route defines its length [9]). Thus, the number of routes with length 2 is defined by the second power of matrixes $\mathbf{[AM]^2}$, $\mathbf{[AM]^3}$ – number of routes with length 3, and so on.

$$[AM]^2 = \begin{bmatrix} 2 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 2 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 3 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 3 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 2 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 3 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \quad [AM]^3 = \begin{bmatrix} 0 & 3 & 4 & 1 & 1 & 2 & 1 \\ 3 & 0 & 1 & 4 & 2 & 1 & 0 \\ 4 & 1 & 2 & 2 & 4 & 5 & 1 \\ 1 & 4 & 2 & 0 & 1 & 5 & 3 \\ 1 & 2 & 4 & 1 & 2 & 4 & 1 \\ 2 & 1 & 5 & 5 & 4 & 2 & 0 \\ 1 & 0 & 1 & 3 & 1 & 0 & 0 \end{bmatrix}$$

$$[AM]^4 = \begin{bmatrix} 7 & 1 & 3 & 6 & 6 & 6 & 1 \\ 1 & 7 & 6 & 1 & 2 & 7 & 4 \\ 3 & 6 & 13 & 7 & 7 & 8 & 2 \\ 6 & 1 & 7 & 12 & 7 & 3 & 0 \\ 6 & 2 & 7 & 7 & 8 & 7 & 1 \\ 6 & 7 & 8 & 3 & 7 & 14 & 5 \\ 1 & 4 & 2 & 0 & 1 & 5 & 3 \end{bmatrix}$$

The obtained calculation results provide a lot of useful information.

- Each matrix row defines the number of routes with length l, connecting the node with the number corresponding to the row number, with the remaining nodes (also with itself).
- If the matrix element $\boldsymbol{am_{ij}}$, for the first time, assumes value different from zero for the matrix power equal to $\boldsymbol{l}$, it means that the minimum length of the path linking the ***i***-th node with the ***j***-th one is ***l***.
- On the basis of obtained results it is possible to determine the graph diameter and the average path length.

Diameter of a coherent graph is the distance between two most distant vertices of the graph, that is, the smallest number ***n*** such that two randomly chosen vertices are connected by a path consisting of maximum ***n*** edges. The diameter is defined by the expression:

$$d(G) = \max_{v_i v_j} \{d_{\min}(v_i, v_j)\} . \qquad (1)$$

The average path length of the graph is defined as the average number of the graph edges connected by any two nodes and is described in the following way:

$$d_{av} = \frac{1}{w(w-1)} \sum_{i=0}^{w-1} \sum_{j=0}^{w-1} d_{\min}(v_i, v_j) \qquad (2)$$

– The sum of all elements occurring in a given row of the matrix is a general number of routes of given lengths that can occur in the analyzed network if a node with the number corresponding to this row is accepted as the source node.
– The sum of all elements occurring in the matrix defines the overall number of routes of given lengths occurring throughout the analyzed network.

In order to simplify and shorten the calculation process (through avoiding the matrix raising to power) it is possible to use repeated multiplying of vector $[V_i]$ describing connections between a chosen source node and the remaining ones, that is, the row corresponding to this node through matrix **[AM]**, that is:

$$\begin{aligned} &[Vi]^2 = [Vi]^1 [AM] \\ &[Vi]^3 = [Vi]^2 [AM] \\ &\ldots \\ &\ldots \\ &[Vi]^j = [Vi]^{j-1} [AM] \end{aligned} \qquad (3)$$

where: ***j*** denotes the route length.

In the analyzed example, shown in fig, 1, vectors describing distributions of routes with lengths 1 to 8, for the source node with number 3, have the form:

$$[V_3]^1 = [0, 1, 0, 0, 0, 1, 1]$$
$$[V_3]^2 = [1, 0, 1, 3, 1, 0, 0]$$
$$[V_3]^3 = [1, 4, 2, 0, 1, 5, 3]$$
$$[V_3]^4 = [6, 1, 7, 3, 12, 7, 3]$$
$$[V_3]^5 = [8, 18, 16, 4, 10, 26, 12]$$
$$[V_3]^6 = [34, 12, 44, 56, 42, 30, 4]$$
$$[V_3]^7 = [56, 90, 106, 46, 74, 142, 56]$$
$$[V_3]^8 = [196, 102, 272, 288, 248, 226, 46]$$

Applying the above observations to the example network, shown in fig.1, it can be said that:

– Accepting an assumption that the node with number 0 is a source node and the length of routes is 3, then table 1 describing a set of these routes to destination nodes has the form:
– Minimal length of the path connecting number 0 node with node1 is 1, with node 2-1, node 3-2, node 4-2, node 5- 2, node 6 – 3, thus, the diameter of graph describing this network is 3.

Table 1. Set of routes to destination nodes

Destination node number							Sum of routes
0	1	2	3	4	5	6	
0	3	4	1	1	2	1	12
Number of routes							

– Average lengths of paths hale been presented in table 2, depending on the accepted source node.

Table 2. Average length of paths

Source node	Average length of paths
0	1,833
1	1,833
2	1,667
3	**1,500**
4	2,000
5	**1,500**
6	2,333

The considered method can be applied in the searching for nodes being roots of minimal spanning trees describing the designed network.

A tree is called a rooted tree if one vertex has been designated as the root. In a rooted tree there is exactly one path between a randomly chosen node and the root. The number of edges in a path his called length, a number with one value higher defines the node level, and the tree height is the highest level existing in a given tree.

To illustrate this, in table 3, there have been given heights of created trees, depending on the choice of the node number, selected as the tree root.

Table 3. Height of spanning trees

Source node	Height of spanning trees
0	3
1	3
2	3
3	**2**
4	3
5	**2**
6	3

The above presented table shows that the tree root should be in node 3 or 5.

In table 4 and in fig. 2 a summary comparison of the number of routes calculated for successively chosen nodes has been given, neglecting routes which form their own loops.

On the basis of received results it can be concluded that the maximum number of routes connecting a chosen node with the other ones, in the possession of node number 5, thus, this node should be selected as the acquisition node location.

With the assumption that this node is a source node, the calculated average length of paths is minimal just as the height of the spanning tree. However, the summary number of bypass routes is maximal which causes an increased probability that the information will reach its address.

Table 4. Summary lengths of routes

Source node	Length of route					
	1	2	3	4	5	6
0	2	3	12	23	70	152
1	2	3	11	21	64	137
2	3	4	17	33	100	223
3	3	6	16	36	94	222
4	2	4	13	30	82	195
5	**3**	**5**	**17**	**36**	**102**	**233**
6	1	2	6	13	36	82
	Sum number of router					

The considered example is not complicated and benefits from optima choice of location for the acquisition node is insignificant, however, in wide networks, consisting of hundreds nodes, the location of this distinguished node can be important. It will have an influence on the time of packets presence in the network and thereby, on the total time of data collection and error rate. This is of importance in case of ‘Hot-potato’ algorithm application for information transmission and reception.

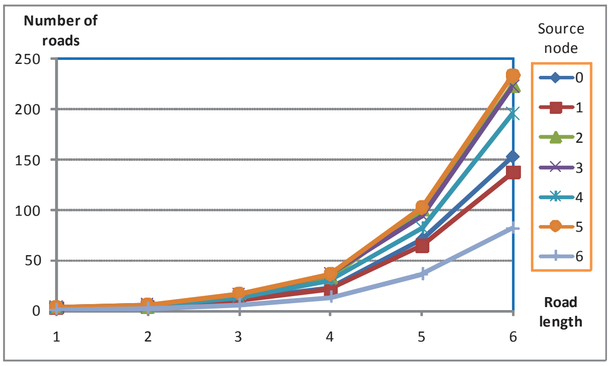


Fig. 2. Summary distribution of router depending on the accepted source node

3. ANALYSIS OF PROBABILITIES

The above presented network analysis has been used for determination of probability for the information to reach its destination node from the source node with a defined route length assumed. The coefficient defining this probability has been calculated by dividing the vector element specifying the number of routes corresponding to the chosen node by a summary number of routes with given lengths.

$$p_{ri}(m) = \frac{r_i}{\sum_{i=0}^{n-1} r_{ri}} \qquad (4)$$

where:

$p_{ri}(m)$ – probability of reaching the i-th node by information, after having covered the m edge of graph,

r_i – number of routes connected source node and chosen node with length m.

Referring to the considered example, the results shown in table 5 and fig. 3 have been obtained for source node number 3.

Table 5. Probability of reaching a given node depending on the route length

Route length	Destination node						
	0	1	2	3	4	5	6
1	0,000	0,333	0,000	0,000	0,000	0,333	0,333
2	0,167	0,000	0,167	0,500	0,167	0,000	0,000
3	0,063	0,250	0,125	0,000	0,063	0,313	0,188
4	0,167	0,028	0,194	0,333	0,194	0,083	0,000
5	0,085	0,191	0,170	0,043	0,106	0,277	0,128
6	0,153	0,054	0,198	0,252	0,189	0,135	0,018
7	0,098	0,158	0,186	0,081	0,130	0,249	0,098
8	0,142	0,074	0,197	0,209	0,180	0,164	0,033
9	0,107	0,138	0,192	0,107	0,142	0,231	0,082
10	0,135	0,087	0,196	0,185	0,173	0,180	0,044
	Probability						

The presented chart proves that if the route length exceeds value 20 which corresponds to the time period of the packet presence in the network, the probability of reaching particular nodes by the information does not change, in fact. Anyway, if node 3 is the source one, then the probability of reaching node 0 by the information is 0.12, 1 – 0.11, 2 – 0.195, 3 – 0.15, 4 – 0.16, 5 – 0.2, whereas, for node 6 – 0.06. This means that if the packet transferred to a given node will stay in the network for time corresponding to the time needed for covering the distance of ***m*** hops, then it should reach its destination with probability pre-determined by the above discussed method.

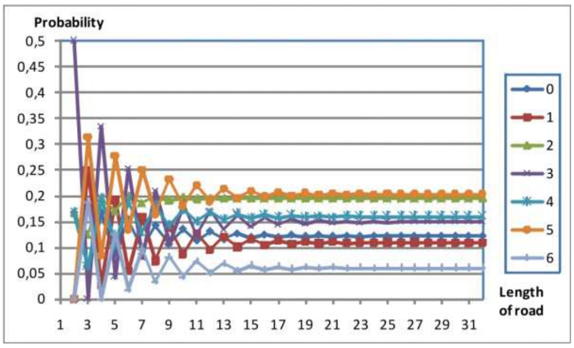


Fig. 3. Probability of reaching a given node depending on the route length

Probability that the packet will reach a given node can also be defined in a different way by creating probability matrix **[*AM_p*]**, describing probability of choosing a given node as the destination one for data transmission.

With reference to the considered example this matrix will have the form:

$$
[AM_p]=\begin{bmatrix}
0.000 & 0.500 & 0.500 & 0.000 & 0.000 & 0.000 & 0.000\\
0.500 & 0.000 & 0.000 & 0.500 & 0.000 & 0.000 & 0.000\\
0.333 & 0.000 & 0.000 & 0.000 & 0.333 & 0.333 & 0.000\\
0.000 & 0.333 & 0.000 & 0.000 & 0.000 & 0.333 & 0.333\\
0.000 & 0.000 & 0.500 & 0.000 & 0.000 & 0.500 & 0.000\\
0.000 & 0.000 & 0.333 & 0.333 & 0.333 & 0.000 & 0.000\\
0.000 & 0.000 & 0.000 & 1.000 & 0.000 & 0.000 & 0.000
\end{bmatrix}
$$

Values of the matrix given elements result from an analysis of the exemplary network which has been shown in fig. 4.

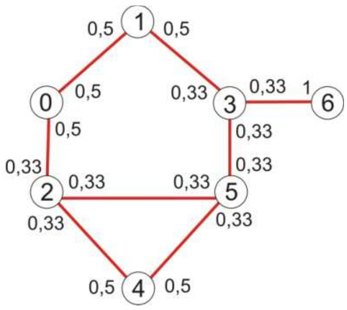


Fig. 4. Distribution of path choice probabilities

Using basic operations to be performed on matrixes it is possible to determine the probability of reaching the destination node by a packet transmitted by a randomly chosen acquisition node, for set time of the packet presence in the network (this time corresponds to the number of hops as this packets has to travel between the source and the destination nodes).

Table 6. Probability of reaching destination by the packet sent by a given acquisition node

	Number of destination node						
Hops number	0	1	2	3	4	5	6
1	0.000	0.333	0.000	0.000	0.000	0.333	0.333
2	0.167	0.000	0.111	0.611	0.111	0.000	0.000
3	0.037	0.287	0.139	0.000	0.037	0.296	0.204
4	0.190	0.019	0.136	0.446	0.145	0.065	0.000
5	0.055	0.244	0.189	0.031	0.067	0.266	0.149
6	0.185	0.038	0.150	0.359	0.152	0.107	0.010
7	0.069	0.212	0.204	0.065	0.085	0.246	0.120
8	0.174	0.056	0.159	0.308	0.150	0.132	0.022
9	0.081	0.190	0.206	0.094	0.097	0.230	0.103
10	0.163	0.072	0.166	0.274	0.145	0.148	0.031

In order to check the obtained results one can calculate the probability of reaching destination by the packet from node 3 to node 0 by routes with length of 4 hops.

Table 7. Calculations concerning the packet probability of reaching its destination

Route	Probability
3 – 6 – 3 – 1 – 0	$\frac{1}{3}\cdot 1\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{18}$
3 – 1 – 3 – 1 – 0	$\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{36}$
3 – 5 – 3 – 1 – 0	$\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{54}$
3 – 1 – 0 – 1 – 0	$\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{2}\cdot\frac{1}{2}=\frac{1}{24}$
3 – 5 – 4 – 2 – 0	$\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{3}=\frac{1}{54}$
3 – 1 – 0 – 2 – 0	$\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{2}\cdot\frac{1}{3}=\frac{1}{36}$
Result	0.190

The obtained results are similar to the results obtained with the use of the above presented method and it can be said that the quantities of probabilities stabilize after having covered by the packet 20 edges of the graph describing the analyzed network (fig.5).

The so far carried out network analysis has not provided any answer to the question – what is the resultant probability for the transmitted packets to reach the destination node. In order to find the answer probability matrixes were used again introducing the following modification. If the transferred package reaches its destination, its further transmission, regardless of the distance it has covered, does not make sense, therefore in the row of $[AM_p]_m$ matrix corresponding to the number of the destination node, there are placed zeros, which means that this node will not transmit the received information to other nodes.

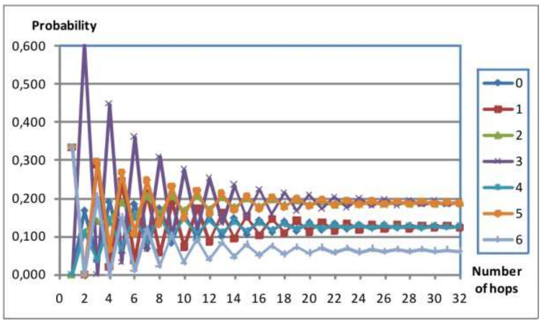


Fig. 5. Distribution of the packet probabilities of reaching its destination nodes

For instance, if the destination node is node 0, then no matter which node is the source one, probability matrix will be of the form:

$$\left[AM_p\right]_m = \begin{bmatrix} 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.500 & 0.000 & 0.000 & 0.500 & 0.000 & 0.000 & 0.000 \\ 0.333 & 0.000 & 0.000 & 0.000 & 0.333 & 0.333 & 0.000 \\ 0.000 & 0.333 & 0.000 & 0.000 & 0.000 & 0.333 & 0.333 \\ 0.000 & 0.000 & 0.500 & 0.000 & 0.000 & 0.500 & 0.000 \\ 0.000 & 0.000 & 0.333 & 0.333 & 0.333 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 & 0.000 & 0.000 & 0.000 \end{bmatrix}$$

In fig. 6 the above discussed reasoning has been demonstrated.

Having done multiplication of vectors by matrix $[AM_p]_m$, the distribution of the packet probability to reach a given node was calculated, depending on the distance covered by it which, as it has already been mentioned, will correspond to the time of the packet presence in the network. As compared to the previously analyzed case, the number of possible routes decreases as there will be eliminated those routes for which node with number 0 performed the function of the transit one.

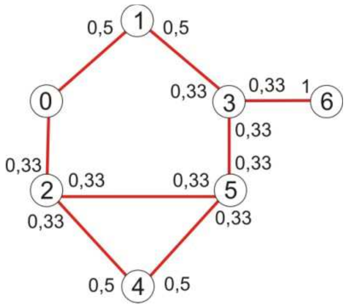


Fig. 6. Distributions of the packet route choice probability

Table 8. Calculation of resultant probability for the packet to reach node 0 from node 3 if the distance length is 4.

Route	Probability
3 – 6 – 3 – 1 – 0	$\frac{1}{3}\cdot 1\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{18}$
3 – 1 – 3 – 1 – 0	$\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{36}$
3 – 5 – 3 – 1 – 0	$\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{2}=\frac{1}{54}$
3 – 5 – 4 – 2 – 0	$\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{2}\cdot\frac{1}{3}=\frac{1}{54}$
Result	0.120

In the table 9 and the figure 7, the distribution of probability of reaching destination by the packet sent from node 3 to destination node 0 has been shown, depending on the number of hops covered by this packet.

In charts presented in fig. 8, calculated distributions of the packet probability to reach its destination node in the function of the number of hops, have been shown for the case when node 5 which, according to the earlier analysis, should be an acquisition node, is a source node.

Table 9. Distribution of the packet probability to reach its destination depending on the number of hops to cover.

Hops number	Probability	Resultand probability	Hops number	Probability	Resultand probability
1	0.000	0.000	16	0.025	0.816
2	0.167	0.167	17	0.017	0.833
3	0.037	0.204	18	0.019	0.852
4	0.120	0.324	19	0.014	0.866
5	0.039	0.363	20	0.015	0.881
6	0.091	0.454	21	0.011	0.893
7	0.036	0.491	22	0.012	0.905
8	0.069	0.560	23	0.009	0.914
9	0.033	0.593	24	0.010	0.923
10	0.053	0.646	25	0.008	0.931
11	0.028	0.674	26	0.008	0.939
12	0.041	0.715	27	0.006	0.945
13	0.024	0.739	28	0.006	0.951
14	0.032	0.771	29	0.005	0.956
15	0.020	0.791	30	0.005	0.960

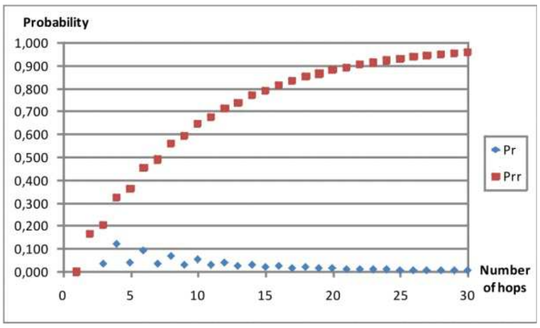


Fig. 7. Chart of the packet probability to reach its destination node, depending on the number of hops. Pr – probability for a given number of hops, Prr – resultant probability.

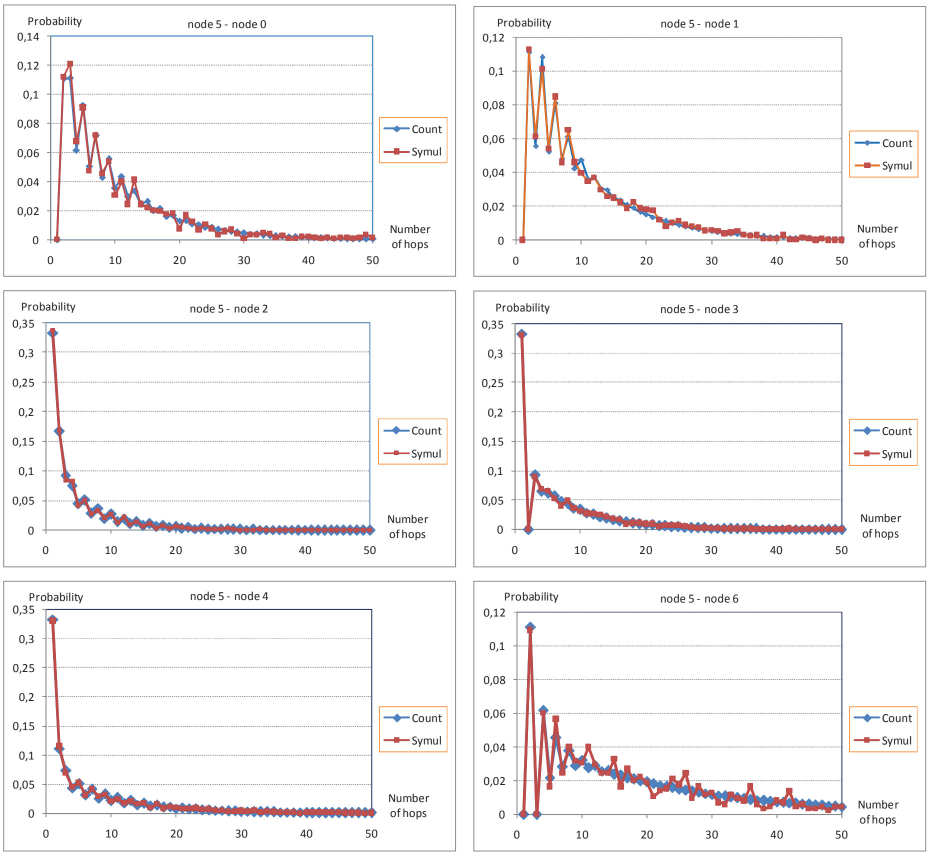


Fig. 8. Distribution of the packet probability to reach its destination node for the case when the destination node is node 5

4. SIMULATIONS

To verify the demonstrated solution to the problem, a computer simulation of a virtual network, shown in fig 1, has been performed, calculating the probability of the packets reaching selected destination nodes, and comparing the obtained results with the theoretically calculated results. In charts (fig.8) the above mentioned distributions obtained from tests performed with the use of a simulation program developed by the authors, have also been given. These tests have proved the rightness of the carried out studies.

Transmission of information takes place in two directions. Reception of the packet by a destination node triggers the process of the return packet transmission which contains information on the node state. Thus, it is also necessary to define the number of hops necessary for transmission of the return information from the destination node to the acquisition one. From the performed calculations it results that the packet, theoretically, should reach the nodes of the analyzed network with probability 0.95 or 0.98 if the number of hops is larger than that, given in table 10.

Table 10. Calculation of the number of hops for which the packet should reach the destination node with the assumed probability

		Source node						
Probability	Destination node	0	1	2	3	4	5	6
0.95	0	-	23	26	28	28	29	29
	1	24	-	30	26	31	30	27
	2	17	20	-	21	13	16	22
	3	23	19	24	-	24	22	1
	4	30	31	25	31	-	25	32
	5	17	18	14	17	11	-	18
	6	65	62	66	56	66	64	-
0.98	0	-	31	34	37	37	37	38
	1	33	-	39	35	40	39	36
	2	23	26	-	27	19	22	28
	3	30	25	31	-	31	29	1
	4	39	40	34	40	-	34	41
	5	22	23	19	21	16	-	22
	6	85	81	86	75	86	84	-

Calculation results and the results obtained in effect of carried out simulations concerning probability of return transmission to node 5, have been demonstrated in figure 9.

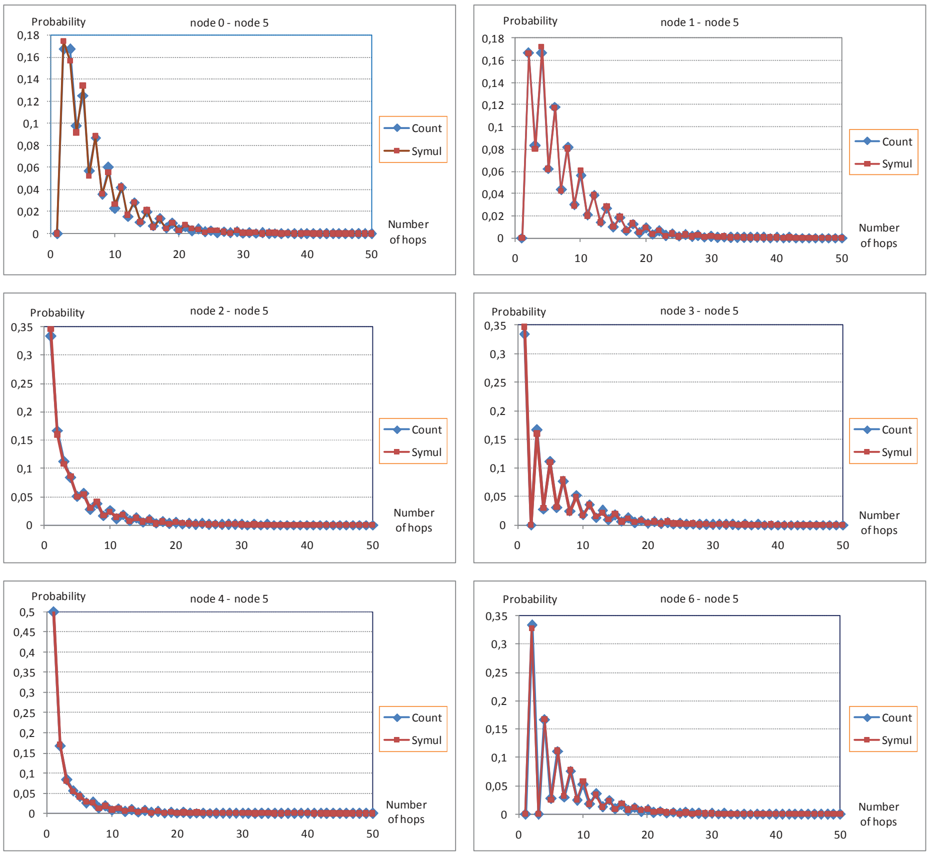


Fig. 9. Distribution of probability for the return packet to reach the destination acquisition node

Summing up the obtained results contained in table 10, the number of hops necessary to transmit and receive a packet to/from nodes has been calculated, with assumed probability of the packet reaching its destination nodes. These results have been included in tables 11 and 12. After having multiplied them by the time needed to transmit the packet to successive nodes, one can calculate time necessary for reception of return information that is, time of waiting for the answer, after which transmission of the next packet will follow.

The obtained results confirm the earlier statement that the optimal location of an acquisition node is node 5 as the total time of the transmitted from this node packet presence, counting from its transmission to its reception, is relatively the shortest.

The main drawback of the 'Hot-Potato' algorithm is lack of certainty whether the packet will reach its destination node. The transmitted packet, apart from the information and control elements, is supplied only with addresses of nodes: source node, transit node and the destination one. This packet can move in the network in both directions "forward" and "backward". In a special case it can oscillate between a certain set of nodes and never reach its destination. To avoid such a situation it is necessary to define the packet life time after which it is removed from the network and another packet should be sent instead. This time, calculated with the use of the considered method, will be equal to the sum of maximum periods of time of the package presence in the network, for both directions of transmission, with the assumed probability for the return packet to reach the source node.

Table 11. Calculation of the total number of hops for which the packet should come back to the sink node with the assumed probability

Resultant probability	Destination node	Sink node						
		0	1	2	3	4	5	6
0,90	0	0	47	43	51	58	46	94
	1	47	0	50	45	62	48	89
	2	43	50	0	45	38	30	88
	3	51	45	45	0	55	39	57
	4	58	62	38	55	0	36	98
	5	46	48	30	39	36	0	82
	6	94	89	88	57	98	82	0
	Total hops number	339	341	294	292	347	281	508

Table 12. Calculation of the total number of hops after which the transmitted packet should come back to the sink node with the assumed probability

Resultant probability	Destination node	Sink node						
		0	1	2	3	4	5	6
0,96	0	0	64	57	67	76	59	123
	1	64	0	65	60	80	62	117
	2	57	65	0	58	53	41	114
	3	67	60	58	0	71	50	76
	4	76	80	53	71	0	50	127
	5	59	62	41	50	50	0	106
	6	123	117	114	76	127	106	0
	Total hops number	446	448	388	382	457	368	663

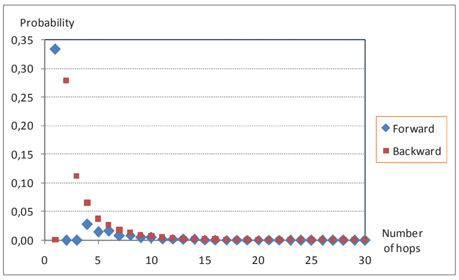
There is one more case that should be accounted for, when the transmitted packet will return to the source node before the assumed time designed for information transmission. Then, it is necessary to analyze data included in the received packet. If this information comes from the destination node it means that transmission has been successfully completed and it is possible to go on to examine the successive node. If the received packet was sent by the source node, removal of this packet and its repeated transmission with TTL (Time To Live) value should follow in order to shorten the time of information exchange and increase probability of achieving the effect of positive transmission.

Probability of occurrence of such a situation can be determined by multiplying vectors, describing probability for the information sent from the source node to reach destination nodes, by a modified probability matrix. Summing values of the resultant vector elements, characteristic for the above mentioned nodes, probability of reaching its destination node by the transmitted packet and probability of the packet return to the source node in the function of covered by this packet distance length, can be determined.

For example in table 13, calculated results of the considered probabilities have been shown in the function of the number of hops for nodes 5 (source) and 3 (destination).

Table 13. Distribution of probabilities of reaching destination node by the packet depending on the number of hops

Hops number	Probability of reaching node 3	Probability of return to node 5	Resultant probability
1	0,3333	0,00000	0,33333
2	0,0000	0,27778	0,61111
3	0,0000	0,11111	0,72222
4	0,0278	0,06481	0,81481
5	0,0139	0,03704	0,86574
6	0,0162	0,02623	0,90818
7	0,0081	0,01698	0,93326
8	0,0083	0,01260	0,95415
9	0,0041	0,00836	0,96666
10	0,0042	0,00626	0,97708
11	0,0021	0,00417	0,98333
12	0,0021	0,00313	0,98854
13	0,0010	0,00208	0,99167
14	0,0010	0,00156	0,99427
15	0,0005	0,00104	0,99583
16	0,0005	0,00078	0,99714
17	0,0003	0,00052	0,99792
18	0,0003	0,00039	0,99857
19	0,0001	0,00026	0,99896
20	0,0001	0,00020	0,99928
21	0,0001	0,00013	0,99948
22	0,0001	0,00010	0,99964
23	0,0000	0,00007	0,99974
24	0,0000	0,00005	0,99982
25	0,0000	0,00003	0,99987
26	0,0000	0,00002	0,99991
27	0,0000	0,00002	0,99993
28	0,0000	0,00001	0,99996
29	0,0000	0,00001	0,99997
30	0,0000	0,00001	0,99998
Sum	0,42423	0,57574	



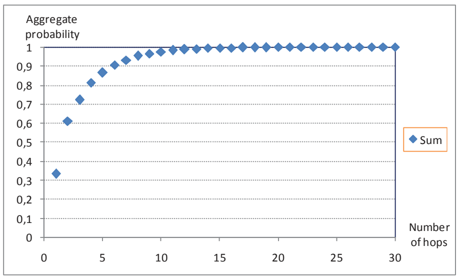


Fig. 10. Charts of the packet probability to reach the destination node (Forward) and its return to the source node (Backward) and resultant probability (Sum) in the function of hop number

In charts presented in fig. 11, calculated distributions of the packet probability to reach the destination and source nodes in the function of hops number, for a case when node 5 is the source node, and accounting for two direction transmission, have been shown.

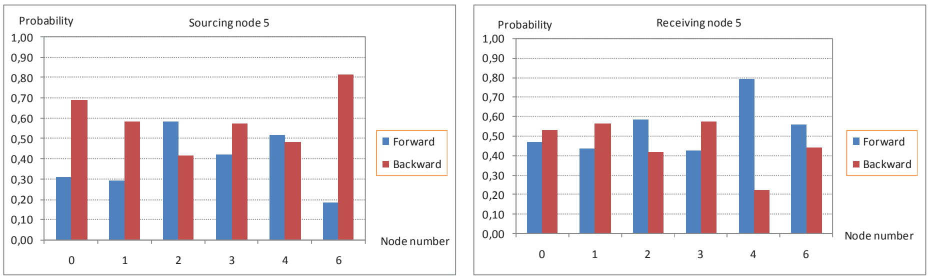


Fig. 11. Distribution of probability to reach by the packet the destination node and its return to the source node versus hop number

The obtained results make it possible to indicate those nodes, sending packets to which will be connected with an assessment of their risk of their return to the transmission node. An analysis of these results can enable an increase in this uncertainty through modification of the network thanks to the rising number of acquisition nodes.

5. CONCLUSIONS

In the paper we have studied the applicability of the “Hot-Potato” protocol in Wireless Sensor Networks, by providing a graph theory based analysis. Two aspects have been focused upon.

First, we have presented a methodology of using adjacency matrixes for calculation of the discussed networks basic parameters – their diameter mean length of paths, and for finding a root of the minimal spanning tree.

This has then been used to study the probability of reaching the destination nodes by transmitted packets and indirect calculation of time for the packets in the network with the assumed probability of a two direction (question-answer) transmission accomplishment.

On the basis of the obtained results it is possible to make a choice of an optimal location for an acquisition node, thanks to which the time of the packet stay in the network will be minimal, which again will shorten the time for data collection, limit emission of radio waves, and minimize the error rate. The carried out theoretical studies, have been verified by using a computer simulation which confirmed the correctness of the considerations.

These studies assume invariable static transmission conditions. Further works in this field will aim at proving usefulness of this analysis in real conditions when the network parameters are not stable, i.e. during transmission of information the links undergo change their parameters, which is connected with reflections, interferences, and wave absorption. It will also be interesting to compare the “Hot-Potato” protocol with other protocols used in Wireless Sensor Networks. Future studies should also address the scalability issues of Wireless Sensor Networks, and include results of much larger networks.

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ANALIZA MOŻLIWOŚCI ZASTOSOWANIA PROTOKOŁU "HOT POTATO" W BEZPRZEWODOWYCH SIECIACH SENSOROWYCH STOSOWANYCH W SYSTEMACH DO MONITOROWANIA ZUŻYCIA ENERGII

Streszczenie

Przedmiotem niniejszego artykułu jest analiza możliwości zastosowania protokołu "Hot-Potato" w bezprzewodowych sieciach sensorowych (WSN), których zadaniem jest zbieranie, przechowywanie i obróbka danych otrzymywanych z liczników monitorujących zużycie mediów. Autorzy proponują zastosowanie tego protokołu ze względu na niską jego emisyjność i niewielką pojemność zastosowanych pamięci przy równoczesnym zachowaniu odpowiedniej niezawodności. W celu dokonania tej analizy wykorzystano elementy teorii grafów.

Słowa kluczowe: bezprzewodowe sieci sensorowe, protokół „Hot Potato", graf, drzewo rozpinające, macierz sąsiedztwa, średnica grafu, średnia długość ścieżki