INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2010, VOL. 56, NO. 3, PP. 215-222
Manuscript received July 10, 2010: revised September, 2010. DOI: 10.2478/v10177-010-0028-x

Bi-criteria Gateway Placement Problem in Wireless Sensor Networks

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Abstract—**Over the last few years, wireless sensor networks (WSNs) have started to play more and more important role in civil and military applications. A typical sensor network consists of resource-constrained sensing nodes, which monitor environment and send the data to more powerful gateway nodes. The goal of gateway nodes is to aggregate, process and send the data to other gateways or directly to sink nodes. The proper placement of nodes is needed to provide good network operation. Sensing nodes are often placed in a random manner unlike gateways. Gateways, due to their role and cost, are installed rather in a controlled way. In this paper, a bi-criteria gateway placement problem is introduced. The problem is shown to be NP-hard. We formulate it as a linear programming problem, then we develop the Multi-criteria Simulated Allocation (MSAL) heuristic algorithm, for the purpose of cost-effective gateway deployment and power-effective wireless connection management. Finally, we evaluate the efficiency of the algorithm by comparison with the exact method.**

Keywords—**Wireless sensor network, bi-criteria optimization, heuristics.**

I. INTRODUCTION

WIRELESS Sensor Networks (WSNs), in a global view, are ad-hoc systems composed of hundreds up to thousands of sensor nodes connected by wireless links. They are used for collecting, processing and disseminating of different types of data. We can find a broad range of potential WSNs' applications including environmental, industrial, agricultural, medical, domestic, and military applications.

Due to the size of such networks, it is intuitive to consider a hierarchical architecture as the target architecture. For this reason we may distinguish different types of nodes in a WSN, e.g. sensor, gateway, base station nodes, and control center.

Sensor nodes are small, usually cheap, spatially distributed, autonomous, and low-power devices equipped with usually irreplaceable batteries with limited power capacity. They have also limited computational capabilities and memory. One of the most important parts of sensor nodes is sensor, a small element used to monitor environmental or physical conditions at different, unattained locations.

Gateway nodes are more "advanced" and "complex". They do not have such constrained computation, communication, and memory resources as sensors. Because of that they are usually more expensive.

Sensor nodes can monitor environmental or physical conditions, collect and aggregate data, whereas gateway nodes can aggregate and process the data collected from all sensor nodes and send the data to a sink node or base station. As we show in the subsequent sections, gateways' locations play a very important role in WSN and have an impact on many parameters of the network.

One of the important problems that designers meet during WSN planning is network lifetime. Life span of a network can be extended thanks to preserving energy of sensor nodes. The longer transmission path from sensor to gateway the more energy is dissipated on relaying of data. Taking this into account, the positions and number of gateway nodes have direct and significant impact on the overall network lifetime by limiting the length of path [14], [11], and [8].

Positions of gateways have also an impact on data collection latency. The problem of reducing the data latency through minimizing the number of hops between a sensor and one of the gateways is defined in [14]. The authors try to calculate the proper gateways' positions within sensor cluster using a genetic algorithm.

Another problem encountered in the WSN design is scalability. Gateways should strive to provide maximal coverage of the area where sensors are deployed. Therefore, there should be the proper number of gateways installed in the network [11]. The problem of maximal coverage and minimal latency is the subject of [1].

In many cases it is desired to minimize the number of gateways due to their cost that can have significant impact on the cost of the network [13]. Gateway location can be calculated within a cluster of sensor nodes, such as in [14], or selected from a set of potential locations. The first approach can be used when we are sure that each calculated location is admissible. But it can happen that the calculated location cannot be used because it is not reachable, so, the second approach is more adequate.

Gateways placement is a difficult optimization problem and due to this fact impossible to be solved by exact methods for large instances of the problem. Many researchers have been working on its mathematical formulation and methods for solving. In the literature known to the authors there is not such approach that takes into account the aforementioned issues, such as: network lifetime depending on energy consumption, traffic delay, cost, and constrained resources of both: sensor and gateway nodes. Thus, in this paper we present an innovative formulation to the gateway placement problem and a simple but efficient heuristic algorithm that provides satisfactory solutions. The objective of our approach is to find the best locations for gateways to provide maximum network lifetime and minimum gateway cost under traffic delay and

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nodes' resources constraints. How to deal with all the issues at the same time? We use a bi-criteria approach. The first of our optimization criteria is minimization of the energy consumed by sensor nodes. The second criterion is minimization of the number of gateways. Both criteria have a direct impact on the minimization of the total network cost. To satisfy delay constraints we propose the usage of a parameter that has direct impact on the delay, namely the length of a path between sensor and gateway nodes, which are measured in the number of hops. Additionally, the hop limit also allows improving the network reliability. Limited capabilities of sensors and gateways resulting from restricted communication, computation, and memory resources can be modeled by a node degree parameter. This parameter says what is the maximum number of active wireless links each sensor and gateway node can serve. It helps to limit the amount of data that can be received by each node what has direct impact on the level of available resources.

The research is a continuation of a previously published work on the design of wireless sensor networks [4], [5]. Our previous research was focused on determining routing paths and gateway locations in WSNs where each node can play a role of sensor and gateway. In current research we assume that each node can be sensor or gateway.

The remainder of the paper is organized as follows. Section II describes our bi-criteria gateway placement problem (BGPP) including network model, presents original linear programming formulation of the problem and analyses its complexity. The proposed MSAL algorithm is described in section III. Numerical results are analyzed in section IV and finally the research is concluded in section V.

II. PROBLEM DESCRIPTION

As described above, we want to find the best number and locations for gateways to provide maximum network lifetime and minimum gateway cost under delay and throughput constraints.

A. Network Model

In the paper we focus on a two level architecture shown in Fig. 1. Sensors are on the first level nodes while gateways belong to the second level nodes.

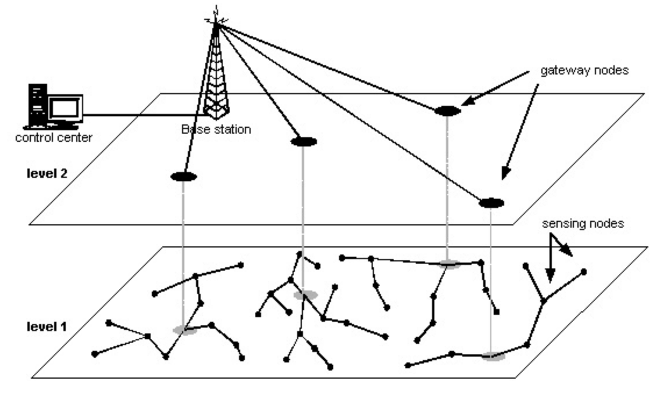

Fig. 1. Reference network model.

We assume that each sensor node performs sensing tasks, gathers data from other nodes, and makes simple data aggregation to eliminate redundancy of information in WSN, therefore minimizing the number of transmissions. All sensor nodes are of the same type. We assume also that they use one-hop broadcast and have predefined transmission range. Their routing table can be updated by gateways. Gateway nodes collect data from sensors, aggregate, process, and send them to control center via satellite or base station. All gateways are of the same type. Gateways can send routing tables calculated in control center to sensors. Sensor and gateway nodes are geographically fixed in a given area and their locations are known. Network topology does not change.

As a radio communication model for sensor nodes we use a simple model for the radio hardware energy dissipation, which is used successfully in [3] and [10]. In the model the transmitter wastes energy to run the radio electronics and the power amplifier while receiver wastes energy to run the radio electronics. Depending on the distance z between the transceiver and receiver, in comparison with a distance threshold z_0, both free space and multipath fading channel models are used. It is assumed in this model, that to transmit one l-bit message over distance z between WSN nodes, the radio has to spend the following amount of energy:

$$E_{Tx}(l,z) = E_{radio\ electronics} + E_{power\ amplifier} = \\ = \begin{cases} l \cdot E_{elec} + l \cdot E_{fs} \cdot z^2 & \text{if} \quad z < z_0 \\ l \cdot E_{elec} + l \cdot E_{mp} \cdot z^4 & \text{if} \quad z \geq z_0 \end{cases} \tag{1}$$

The amount of energy consumed to receive this message is:

$$E_{Rx}(l) = E_{radio\,electronics} = l \cdot E_{elec} \tag{2}$$

E_{elec} – energy consumed per bit in the transmitter or receiver circuitry,
E_{mp} – energy consumed in RF amplifiers to compensate for propagation loss depending on the transmission distance z (for multi-path fading),
E_{fs} – energy consumed in RF amplifiers to compensate for propagation loss depending on the transmission distance z (for free space),
l – length of message in number of bits to be transmitted,
z – distance between WSN nodes over which the message is transmitted,
z_0 – distance threshold on the basis of which free space and multipath fading channel models are used, $z_0 = \text{sqrt}(E_{fs}/ E_{mp})$.

B. Problem Formulation

Let the set $P = (W, E)$ represents an Euclidean graph with the set W of N vertices corresponding to the WSN nodes, which are placed in known locations. Set E of edges represents wireless links between the nodes. E does not contain edges between potential gateways. Our WSN model consists of sensors (small dots in Fig. 2) and potential gateways (big dots in Fig. 2) that can be aggregated into two sets: S and G, respectively. Thus, W is the union of two disjoint sub sets: $W = S \cup G$. All the aforementioned sets are predetermined.

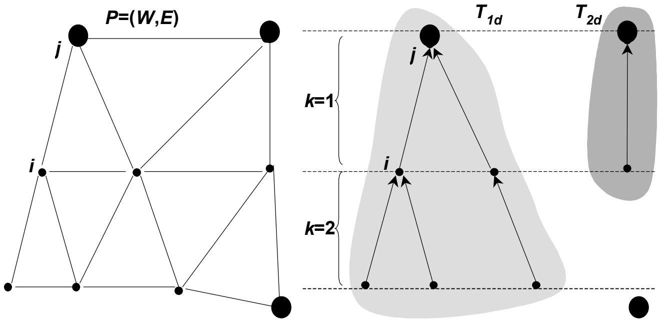

Fig. 2. Graph and forest.

Each edge $\{i,j\}$ in E has assigned cost c_{ij} that represents energy consumption to transmit l-bit message over a distance z (E_{Tx}) (see equation 1). We neglect E_{Rx} because it does not depend on the distance between nodes and represents a constant parameter for the defined WSN and the number of bits to be received. The cost has constant value for each edge in a given graph.

Tree $T_r = (W_{Tr}, E_{Tr})$, where $r = 1, 2, ..., R$, is a connected acyclic subgraph of P, where $W_{Tr} \subseteq S \cup \{g_r\}$, $g_r \in G$. g_r is the root of tree T_r, and represents the gateway node selected for T_r from the set of potential gateways. $E_{Tr} \subseteq E$ contains edges forming tree T_r spanned over nodes from W_{Tr}.

Let's transform such T_r into directed T_{rd} which has edges directed to parent nodes (see trees T_{1d} and T_{2d} in Fig. 2).

Spanning forest $F = \{T_{1d}, T_{2d}, ..., T_{rd}\}$ is a set of R vertex disjoint trees T_{rd}, $r = 1, 2, ..., R$, such that $\bigcup^{R}_{r=1} W_{Trd} = W \backslash \{$non root nodes from $G\}$, $n \neq m \Rightarrow W_{Tnd} \cap W_{Tmd} = \varnothing$. Fig. 2 shows a forest with two calculated trees.

Let's impose constraints on trees T_{rd} in forest F such as path length from sensor to gateway measured in the number of hops and node degree. In our model k is the level index, at which an edge is located at T_{rd}. The maximum value of k equals the maximum possible path length H ($H = k_{max} = 2$ in Fig. 2). D_s is the maximum acceptable value of the sum of outdegrees and indegrees over all sensor nodes, while D_g is the maximum acceptable value of the sum of outdegree and indegree of gateway nodes ($D_s = D_g = 3$ in Fig. 2).

The objective of the bi-criteria gateway placement problem (BGPP) is to find such a "forest of trees" that simultaneously minimizes the sum of energy E_{Tx} consumed by transmitters of sensors (Equation 1) and the number of gateways under the hops H and degrees D_s and D_g constraints. The problem is formulated as:

indices:

$i, j, n = 1, 2, ..., N$	nodes
$k = 1, 2, ..., H$	levels of edges

constants:

c_{ij} energy needed to transmit l-bit message over a distance z between nodes i and j (E_{Tx} in equation 1)
D_s maximum acceptable sensor node degree
D_g maximum acceptable gateway node degree
H maximum path length between sensor and gateway
s_i = 1 if node $i \in S$, 0 otherwise
g_i = 1 if node $i \in G$, 0 otherwise

variables:

x_{ijk} = 1 if there exists edge (i,j) on level k, 0 otherwise
y_i = 1 if node i is selected as a gateway, 0 otherwise

objectives:

$$\min \sum_i \sum_j s_i c_{ij} \sum_k x_{ijk} \tag{3}$$

$$\min \sum_i g_i y_i \tag{4}$$

constraints:

$$\sum_{i,\, i \neq j} s_i x_{ij1} - D_g g_j y_j \le 0, j = 1, 2, ..., N \tag{5}$$

$$\sum_{j,\, j \neq i} \sum_k s_i x_{ijk} = 1, i = 1, 2, ..., N \tag{6}$$

$$\sum_{i,\, i \neq j} \sum_k s_i x_{ijk} \le D_s - 1, j = 1, 2, ..., N \tag{7}$$

$$s_i s_j x_{ijk+1} - \sum_n s_j x_{jnk} \le 0,\ k = 1, 2, ..., H-1,\ i = 1, 2, ..., N,\ j = 1, 2, ..., N \tag{8}$$

x_{ijk} and y_i variables are binary (9)

Objective function (3) returns the total cost of the designed sensor network, which is the sum of energy E_{Tx} consumed by transmitters of sensors. The second objective (4) returns the total number of gateways that are needed to connect all sensors in "trees".

Constraint (5) ensures that if node j is not a gateway, then there are no arcs directed to j, which is on the first level ($k = 1$). But if j is a gateway, indegree of j cannot exceed D_g. Constraint (6) forces only one edge on any level k can be outgoing edge at sensor node i. Inequality (7) ensures that indegree of sensor node j cannot exceed D_s-1. Constraint (8) assures the existence of an edge on (k+1)th level only if there is an edge on kth level.

C. Problem Complexity

Above formulated gateway placement problem belongs to the set of NP-hard. This classification can be done because it incorporates two NP-hard problems: hop constrained [9] and degree constrained [6] minimum spanning tree problems, which can be reduced to our problem.

Moreover, BGPP is additionally complicated by the fact that it belongs to the class of multi-criteria optimization problems. Two objectives: minimization of the energy consumption and the number of gateways, which conflict with each other, affect the complexity of the problem.

In the next sections we use terminology associated with multi-criteria optimization, so, it seems to be reasonable to present some basic terms:

Definition 1:
Solution of multi-criteria problem, for which there are no solutions which enhance the value of one criterion without worsening the value of another, is called Pareto optimal solution.

Definition 2:
Solution X is called dominated if there is a feasible solution Y, which is at least as good as X for each criterion, and better than X for at least one criterion.

A conclusion that can be made on the basis of definition 1 and 2 is as follows: Pareto optimal solution is non-dominated solution.

Definition 3:
Collection of all the values of objective functions, obtained after solving a multi-criteria task, for which the corresponding vectors of decision variables belong to the set of Pareto optimal solutions, is called Pareto frontier.

III. MSAL ALGORITHM

As BGPP is NP-hard problem and it is impossible to be solved by exact methods for large problem instances, we propose a simple, adaptive and efficient heuristic method, called the Multi-objective Simulated Allocation (MSAL) to solve this problem. The algorithm bases on its single-objective version, which is presented in [12] and [7].

At the beginning, the algorithm initializes graph P with the set W of WSN nodes, and the set E of edges representing wireless links between the nodes. Set W is the union of two disjoint sub sets of sensors (S) and gateways (G): $W = S \cup G$, $S \cap G = \emptyset$. Depending on the nature of WSN there are different ways of generating W and calculating E. We assumed in our research that W is generated by random choice of coordinates of sensors and gateways in two-dimensional space. The space is limited to a rectangular area. E is a set of existing wireless links between nodes. Energy dissipation that is determined with the usage of equation 1 for each pair of nodes, which are in the transmission range, represents cost assigned to each edge. In the next step MSAL initializes *Pareto* set to keep all Pareto solutions calculated by algorithm. The set is empty at the beginning. The algorithm defines also *step* variable (counter of iterations) and the following initialized by the user:

- *limit* – maximum number of iterations,
- *percentage* – percentage of nodes that have to be disconnected during *disconnect* procedure,
- H – maximum acceptable path length,
- D_s – maximum acceptable degree of sensor nodes,
- D_g – maximum acceptable degree of gateway nodes.

Then, the algorithm runs *allocate* procedure and assigns the solution to *Pareto* set. After this step, *disconnect* and *allocate* methods are run sequentially a predefined number of times. After *allocate* procedure, the algorithm verifies if obtained solution is non-dominated and updates *Pareto* set if needed. MSAL pseudo-code is presented in Fig. 3.

```
initialize: $P=(W,E)$, $W=S\cup G$, $S\neq\emptyset$, $G\neq\emptyset$, $Pareto=\emptyset$, $step=1$,
    $limit\neq 0$, $H\neq 0$, $D_s\neq 0$, $D_g\neq 0$, $percentage\neq 0$
allocate nodes to create forest $F_{step}$
update Pareto
repeat
    randomly disconnect percentage of nodes from $F_{step}$
    allocate nodes to create forest $F_{step}$
    if new solution is non-dominated then update Pareto
    step++
until $step = limit$
```

Fig. 3. Pseudo-code of MSAL algorithm.

```
allocate procedure:
initialize: $L=\emptyset$, $allocated=0$
repeat
    choose randomly node $i$ from $W$
    if $i \in G$ then make $i$ as gateway and $allocated=1$
    else if neighbor of $i \in F_{step}$ and neighbor degree$<D$ and
        neighbor path$<H$ and $c_{i\ neighbor}$ is minimum then add $i$ to $F_{step}$
        and $allocated=1$
    else add $i$ to $L$
    if $allocated=1$ then $L=\emptyset$
until $S!=\emptyset$
```

Fig. 4. Pseudo-code of *allocate* procedure.

A*llocate* procedure, which is presented in Fig. 4 as a pseudo-code, starts with the initialization of set of tabu nodes L and *allocated* variable. After this step, it selects randomly nodes from the set W and checks if they belong to S or G. Then, depending on the membership, the status of neighboring nodes, and D_s, D_g, and H constraints, and the distance the method decides if the node should be selected as a gateway, non-gateway in tree T_r, or returned to W.

Disconnect procedure removes randomly a predefined *percentage* of the nodes from forest F_{step}.

IV. NUMERICAL RESULTS

To evaluate the quality of the MSAL algorithm, we carried out some numerical experiments. In our tests we used uniform random Euclidean graphs [2] with a) 10 sensors and 5 gateway nodes (P1), b) 10 sensors and 15 gateway nodes (P2), c) 100 sensors and 30 gateway nodes (P3), d) 100 sensors and 40 gateway nodes (P4). All the nodes were randomly distributed in a square grid of dimension 300m by 300m for case a) and b), and 500m by 500m for case c) and d). We used graphs of different size with different proportion of sensor to gateway node number to check how our algorithm copes with different instances of graphs. We assumed that the amount of energy consumption during transmission (see equation 1) of 1bit packet over distance z, is assigned as a cost to wireless link between sensor nodes. Distance z is a value of ceiling function of Euclidean distance between the coordinates of points representing sensor and gateway nodes. Maximum distance between nodes was 100m. The parameters of energy were set up as E_{elec} = 50nJ/bit, E_{fs} = 10pJ/bit/m^2, E_{mp} = 0,001pJ/bit/m^4. The values used by us in the experiments were also successfully used in [3] and [10]. Simulations were performed for $D_s = D_g = D = 3$ and $H = 2$. We are aware that D_s, D_g, and H values may have an impact into the results. However, for definiteness, we use the above values to focus mainly on different input graphs and the impact of *percentage* parameter on the results. To check the impact of MSAL *percentage* parameter on the quality of results we used the following values of the parameter during tests: case1 – 10%, case2 – 80%, and after 1000 iterations 100%, case3 – 100%. *Limit* parameter was set to 50000. Due to the nature of our algorithm that gives near optimal solutions in most cases, each experiment was performed 10 times to estimate distribution of solutions. We used minimum, maximum and average values during the analysis of the results.

TABLE I
PARETO-OPTIMAL SOLUTIONS OBTAINED FOR P1 AND P2

graph	algorithm	No. of gateways	Min. cost	Max. cost	Avg. cost
P1	CPLEX	2	855	-	-
		3	792	-	-
		4	760	-	-
		5	743	-	-
P1	MSAL case1	2	855	909	880,5
		3	792	792	792
		4	760	760	760
		5	743	743	743
P1	MSAL case2	2	855	855	855
		3	792	792	792
		4	760	760	760
		5	743	743	743
P2	CPLEX	2	836	-	-
		3	739	-	-
		4	662	-	-
		5	645	-	-
		6	630	-	-
		7	619	-	-
P2	MSAL case1	4	662	662	662
		5	645	645	645
		6	630	630	630
		7	618	618	618
P2	MASL case2	2	927	1008	956,4
		3	739	742	739,6
		4	662	662	662
		5	645	645	645
		6	630	630	630
		7	618	618	618
P2	MASL case3	2	836	939	898,2
		3	739	739	739
		4	662	662	662
		5	645	645	645
		6	630	630	630
		7	618	618	618

Table I includes Pareto optimal solutions found by MSAL and CPLEX for graphs P1 and P2. As it can be observed in the case of P1, MSAL algorithm run with case2 parameters gives all optimal solutions in each of 10 test trials. Cost results obtained thanks to MSAL with case1 parameters are optimal for 3, 4, and 5 gateways in each of 10 test trials. However, Pareto optimal solution for minimum number of gateways was received 3 times during 10 test trials. It can be caused too low diversification of the algorithm or, on the other hand, too high number of potential gateways.

Analyzing the results obtained for P2 graph, where we generated three times more potential gateways, we can see the same regularity as in case of the previous graph. Therefore, MSAL with case1 parameters could not find solutions with 2 and 3 gateways, but it found optimal costs for 4, 5, 6, and 7 gateways. Following this path we can see that MSAL with case2 parameters found optimal costs for 3 gateways. The conclusion is the same as in the previous section: to obtain Pareto optimal solutions we have to increase diversification of the algorithm or, on the other hand, decrease the number of potential gateways.

Comparing results for P1 and P2 graphs it can be seen that MSAL works better for more limited number of locations for potential gateways.

Additionally we present in Fig. 5 and 6 Pareto frontiers calculated by MSAL and CPLEX for graphs P1 and P2 as bar charts. The figures show the energy consumption by all sensor nodes in WSN to transmit 1 bit of data as a function of the number of gateway nodes determined for the network. On the first view we can notice that energy consumption by sensor nodes is lower for higher number of determined gateways. MSAL algorithm correctly calculated most Pareto optimal solutions comparing to CPLEX (black columns in Fig. 5 and 6). The only difficulty was to get minimum energy consumption by minimal number of gateways (see the values of consumed energy for the network with 2 gateways in Fig. 5 and 6). Fig. 6 also shows that MSAL for the case1 parameters did not calculate solutions where the number of gateways equals 2 and 3. As it was mentioned before it is due to low diversification of the algorithm.

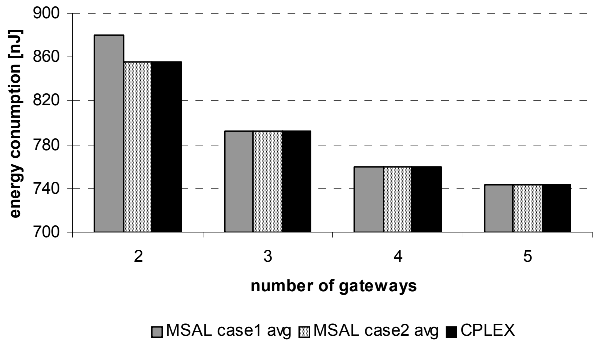

Fig. 5. Pareto frontier as bar chart (energy consumption by varying number of gateways) for CPLEX (optimal solutions) and MSAL case1 and case2 (average energy consumption); graph P1.

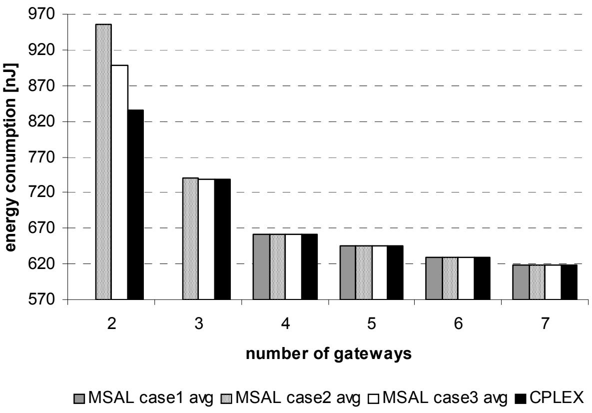

Fig. 6. Pareto frontier as bar chart (energy consumption by varying number of gateways) for CPLEX (optimal solutions), MSAL case1, case2 and case3 (average energy consumption); graph P2.

Table II includes solutions found by MSAL for graph P3. As it can be seen, MSAL algorithm run with case3 parameters gives the largest set of Pareto solutions comparing with sets of solutions calculated by MSAL with case1 and case2 parameters. Due to slower convergence of MSAL with case2 and case3 parameters because of its higher diversification, the calculated energy consumption is in some cases 5% higher in comparison with the values calculated by MSAL with case1 parameters.

TABLE II
PARETO-OPTIMAL SOLUTIONS OBTAINED FOR P3

graph	algorithm	No. of gateways	Min. Cost	Max. cost	Avg. cost
P3	MSAL case1	19	6709	7681	7010,8
		20	6559	6683	6625,4
		21	6410	6551	6490,9
		22	6353	6425	6394
		23	6317	6383	6355
		24	6308	6343	6325
		25	6306	6363	6330,4
		26	6327	6327	6327
P3	MSAL case2	17	7234	7556	7392,3
		18	6949	7210	7061,9
		19	6663	6932	6827,4
		20	6542	6763	6695,7
		21	6521	6625	6596,3
		22	6444	6582	6517,9
		23	6455	6530	6489,8
		24	6399	6510	6469,2
		25	6414	6498	6461,5
		26	6491	6491	6491
P3	MSAL case3	16	7527	8040	7758
		17	7245	7775	7590,3
		18	7000	7387	7184,7
		19	6934	7101	6996,8
		20	6757	6907	6855,9
		21	6719	6830	6762,2
		22	6517	6766	6663,3
		23	6642	6699	6676,6
		24	6526	6657	6602,6
		25	6606	6618	6612
		26	6624	6624	6624

TABLE III
PARETO-OPTIMAL SOLUTIONS OBTAINED FOR P4

graph	algorithm	No. of gateways	Min. Cost	Max. cost	Avg. cost
P4	MSAL case1	22	6521	6544	6532,5
		23	6399	6669	6494,6
		24	6224	6378	6289,6
		25	6177	6262	6205,9
		26	6085	6199	6154,5
		27	6095	6148	6121,4
		28	6038	6122	6075,7
		29	6049	6106	6075,6
		30	6098	6098	6098
		31	6069	6093	6081
		32	6085	6097	6091
P4	MSAL case2	20	6795	7261	7008,9
		21	6604	6787	6725
		22	6428	6610	6539,2
		23	6371	6548	6455,4
		24	6320	6444	6382,1
		25	6258	6386	6322,8
		26	6255	6343	6294,1
		27	6193	6275	6231,9
		28	6191	6239	6222,3
		29	6172	6259	6222,7
		30	6232	6232	6232
P4	MSAL case3	18	8189	8189	8189
		19	7199	7506	7362,9
		20	6717	7125	6998,7
		21	6758	7010	6887
		22	6527	6842	6696,3
		23	6519	6675	6612,6
		24	6458	6663	6579
		25	6494	6548	6523,3
		26	6308	6503	6443,8
		27	6458	6491	6474,4
		28	6343	6466	6412
		29	6467	6467	6467
		30	6378	6403	6390,5
		31	6449	6449	6449

Table III includes solutions found by MSAL for graph P4 with higher number of potential gateways in comparison with P3. In this case, similarly to the case of graph P3, MSAL algorithm run with case3 parameters the largest set of Pareto solutions comparing with sets of solutions calculated by MSAL with case1 and case2 parameters. Due to slower convergence of MSAL with case2 and case3 parameters because of its higher diversification, the calculated energy consumption is in some cases 6,4% higher in comparison with the values calculated by MSAL with case1 parameters.

Fig. 7 presents the average energy consumption as a function of the number of gateway nodes determined for the network obtained for graphs P3 and P4 by means of MSAL with case1 and case3 parameters.

Comparing the results for P3 and P4 graphs it can be seen that higher diversification and lower number of potential gateways help getting lower number of final locations of gateways. Lower energy consumption can be assured by lower diversification.

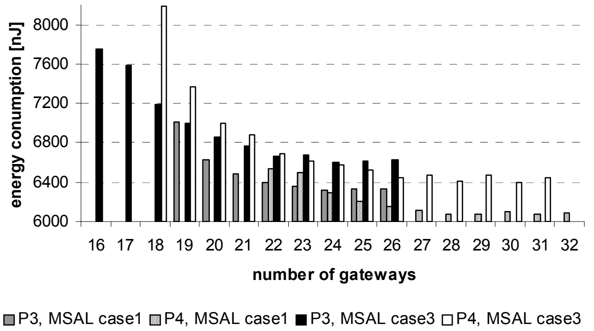

Fig. 7. Pareto frontier as bar chart (energy consumption by varying number of gateways) for P3 (MSAL case1 and case3 - average energy consumption) and P4 (MSAL case1 and case3 - average energy consumption).

V. SUMMARY

The research is a continuation of a previously published work on the design of wireless sensor networks [4], [5]. Our previous research was focused on determining routing paths and gateway locations in WSNs where each node can play a role of sensor and gateway. In current research we assume that each node can be sensor or gateway.

In this paper we focused on gateway placement problem in WSNs. We defined a bi-criteria gateway placement problem (BGPP) taking into account traffic delay, cost, constrained resources of both: sensor and gateway nodes, and energy consumption has an impact into the network lifetime. The objective is to find the best locations of gateways to provide maximum network lifetime and minimum gateway cost under delay and throughput constraints. We have not found any similar formulation to this problem in the literature known to us.

Since BGPP is NP-hard and due to this fact impossible to be solved by exact methods for large instances of the problem, we developed a simple but efficient multi-objective MSAL heuristics. Numerical examples show that it is possible to achieve a set of feasible and satisfactory results for graphs close to real models of WSNs. We obtained optimal solutions for small instances of graphs. Taking into account the presented results we can say that higher diversification of the algorithm and lower number of potential gateways help getting a lower number of final locations of gateways. Lower energy consumption can be assured by lower diversification.

Future studies include regular sensor networks and sensor networks in which sensors do not support data aggregation to eliminate redundancy of information. Future work covers also algorithm improvement and research on applications of the problem to other types of networks, e.g. passive optical networks.

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