An Optimal Node Scheduling for Flat Wireless Sensor Networks

Fabíola Guerra Nakamura, Frederico Paiva Quintão,
Gustavo Campos Menezes, and Geraldo Robson Mateus

Federal University of Minas Gerais – UFMG – Brazil
{fgnaka, fred, gcm, mateus}@dcc.ufmg.br

Abstract. The determination of a topology that minimizes the energy consumption and assures the application requirements is one of the greatest challenges about Wireless Sensor Networks (WSNs). This work presents a dynamic mixed integer linear programming (MILP) model to solve the coverage and connectivity dynamic problems (CCDP) in flat WSNs. The model solution provides a node scheduling scheme indicating the network topology in pre-defined time periods. The objective consists of assuring the coverage area and network connectivity at each period minimizing the energy consumption. The model tests use the optimization commercial package CPLEX 7.0. The results show that the proposed node scheduling scheme allows the network operation during all the defined periods guaranteeing the best possible coverage, and can extend the network lifetime besides the horizon of time.

1 Introduction

A Wireless Sensor Network (WSN) is a special kind of an ad hoc network composed by autonomous and compact devices with sensing, communication, and processing capacities, called sensor nodes [1]. Basically, in a WSN application, the sensor nodes are deployed over an area to collect data from a phenomenon. The data are disseminated from source nodes to sink nodes and then to an observer [2], where they are processed and provide information about the environment.

There are several challenges regarding WSNs once these networks present several particularities as energy restrictions, node redundancy,limited bandwidth, and dynamic topology. These unique features allow a wide variety of research in energy-efficient network protocols, low-power hardware design and encourage proposals of management architectures for WSNs, which aim to increase the network resources productivity, and to maintain the quality of service [3].

This work presents a dynamic mixed integer linear programming (MILP) model, whose solution determines an optimal node scheduling for flat WSNs. The objective function aims to minimize the network energy consumption and the model constraints assure the quality of service requirements such as coverage, connectivity, with respect to nodes energy restrictions. The work contribution

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is a mathematical formulation that models coverage, connectivity, and energy WSNs features, and whose solutions can be inserted in a WSN management scheme.

The remainder of the paper is organized as follows: In the next section we present the model proposed. Section 3 contains the experimental results and their analysis. We list the related work in section 4. In section 5 we present our conclusions and describe the directions of our future work.

2 Dynamic Mixed Integer Linear Programming Model

2.1 Basic Concepts

Coverage in Wireless Sensor Networks. In order to quantify the coverage area of a WSN, we define the node sensing area as the region around the node where a phenomenon can be detected and define this region as a circle of range R, where R is the sensing range [4]. The coverage area of a WSN consists of the sensing areas union of all active nodes in the network.

The coverage area is modelled through the use of demanda points, which represent the center of a small square area in the sensor field. This concept allows to evaluate the coverage in a discrete space and is useful for modelling purposes. To guarantee the coverage, at least one active sensor should cover each demand point, otherwise the coverage fails.

Energy Consumption Model. One of the main features of WSNs is a high energy restriction, due to the limited sensor node battery, and to the impossibility of battery recharge. The definition of a node energy consumption model can allow WSNs researches to focus the studies on topics that have higher impacts on the network lifetime [5]. The node operations consumption depends on the current necessary to perform the task and time period to execute the task. The energy consumed can be estimated by the following equation:

$$E = \alpha \times \Delta t$$

where: E is the total energy consumed in mAh.
α is the current consumed in mA.
Δt is the period of time in h.

The WSN application dependency makes really important that we define a work scenario. On the development of our model we make the following assumptions: each sensor node knows its localization, and has an unique id, the application requirements are continuous data collection and periodic data dissemination, and battery discharge follows a linear model. Only source nodes generate traffic in the network.

2.2 Mathematical Formulation

Our problem can be stated as: *Given a sensor field A, a set of demand points D, a set of sensor nodes S, a set of sink nodes M, and t time periods the coverage* *and connectivity dynamic problem (CCDP) consists of assuring that at least m sensor nodes $i \in S$ are covering each demand point $j \in D$ in the sensor field A, and that there is a path between these nodes, and a sink node $j \in M$ in each time period.*

The CCDP is formulated as a mixed integer linear programming(MILP) problem. The following parameters are used in our formulation:

S set of sensor nodes
M set of sink nodes
D set of demand points
T set of time periods
A^d set of arcs that connect sensor nodes to demand points
A^s set of arcs that connect sensor nodes
A^m set of arcs that connect sensor nodes to sink nodes
$E^d(A)$ set of arcs $(i, j) \in A$ entering on the demand point $j \in D$
$E^s(A)$ set of arcs $(i, j) \in A$ entering on the node $j \in S$
$S^s(A)$ set of arcs $(i, j) \in A$ emanating from the node $i \in S$
n defines the number of nodes the should cover a demand point
BE node battery capacity
AE_i energy to activate a node $i \in S$
ME_i energy to keep a node $i \in S$ active during a time period $t \in T$
TE_ij energy to transmit packets from $i \in S$ to $j \in S$ during a time period $t \in T$
RE_i energy to recept packets in node $i \in S$ during a time period $t \in T$
HE_j penalty of no coverage of a demand point $j \in D$ during a time period $t \in T$

The model variables are:

x^t_{ij} has value 1 if node $i \in S$ covers demand point $j \in D$ on time period $t \in T$, and 0 otherwise
z^t_{lij} has value 1 if arc (i, j) is in the path between sensor node $l \in S$, and a sink node $m \in M$ on time period $t \in T$, and 0 otherwise
w^t_i has value 1 if node $i \in S$ is activated on time period $t \in T$, and 0 otherwise
y^t_i has value 1 if node $i \in S$ is active on time period $t \in T$, and 0 otherwise
h^t_j indicates if demand point $j \in D$ is not covered on time period $t \in T$
e_i indicates the value of the energy consumed by node $i \in S$ during the network lifetime

The model proposed is presented below. The objective function 1 minimizes the network energy consumption during its lifetime.

$$min \sum_{i \in S} e_i + \sum_{j \in D} \sum_{t \in T} EH^t_j \times h^t_j \qquad (1)$$

Constraints (2), (3), (4), and (5) deal with the coverage problem. They assure that the active nodes cover the demand points. Constraints (2) also assure the possibility of a demand point not be covered. A demand point is not covered when it is not in the coverage area of any active node or when the node that could cover it has no residual energy.

$$\sum_{ij \in E_j^d(A^d)} x_{ij}^t + h_j^t \geq n, \forall j \in D \text{ e } \forall t \in T \tag{2}$$

$$x_{ij}^t \leq y_i^t, \forall i \in S, \forall ij \in A^d \text{ e } \forall t \in T \tag{3}$$

$$0 \leq x_{ij}^t \leq 1, \forall ij \in A^d \text{ e } \forall t \in T \tag{4}$$

$$h_j^t \geq 0, \forall j \in D \text{ e } \forall t \in T \tag{5}$$

Constraints (6), (7), (8), and (9) are related to the connectivity problem. They impose a path between each active sensor node and a sink node.

$$\sum_{ij \in E_j^s(A^s)} z_{lij}^t - \sum_{jk \in S_j^s(A^s \cup A^m)} z_{ljk}^t = 0, \forall j \in (S \cup M - l), \forall l \in S \text{ e } \forall t \in T \tag{6}$$

$$- \sum_{jk \in S_j^s(A^s \cup A^m)} z_{ljk}^t = -y_l^t, j = l, \forall l \in S \text{ e } \forall t \in T \tag{7}$$

$$z_{lij}^t \leq y_i^t, \forall i \in S, \forall l \in (S - j), \forall ij \in (A^s \cup A^m) \text{ e } \forall t \in T \tag{8}$$

$$z_{lij}^t \leq y_j^t, \forall j \in S, \forall l \in (S - j), \forall ij \in (A^s \cup A^m) \text{ e } \forall t \in T \tag{9}$$

The node residual energy is defined by constraints (10) which indicate that a node can only be active if it has residual energy, and by (11), and (12), this energy must be nonnegative and less than the battery capacity.

$$\sum_{t \in T}(EM_i \times y_i^t + EA_i \times w_i^t + \sum_{l \in (S-i)} \sum_{ki \in E_i^s(A^s \cup A^m)} ER_i \times z_{lki}^t +$$
$$\sum_{l \in S} \sum_{ij \in S_i^s(A^s \cup A^m)} ET_{ij} \times z_{lij}^t) \leq e_i, \forall i \in S \tag{10}$$

$$e_i \leq EB_i, \forall i \in S \tag{11}$$

$$e_i \geq 0, \forall i \in S \tag{12}$$

The constraints (13), and (14) indicate activation node period.

$$w_i^0 - y_i^0 \geq 0, \forall i \in S \tag{13}$$

$$w_i^t - y_i^t + y_i^{t-1} \geq 0, \forall i \in S, \forall t \in T \text{ e } t > 0 \tag{14}$$

Constraints (15) define the variables y,z, and w as boolean, and constraints (16) define the variables x,h, and e as real.

$$y, z, w \in \{0, 1\} \tag{15}$$

$$x, h, e \in \Re \tag{16}$$

For each time period, the model solution indicates which nodes are actives, which demand points are not covered, and provides a path between the actives nodes and the sink node, guaranteeing the network connectivity. The solution also estimates the network energy consumption.

3 Experimental Results

3.1 Input Parameters

We consider a flat network, and homogeneous nodes. The sensor nodes are deployed over the sensor field in a random way with uniform distribution.

The model input parameters are: one demand point for each m^2, $625m^2$ sensor field, 16 sensor nodes, one sink node in the center or in corner of the area, and coverage guaranteed by $n = 1$ or $n = 2$. The energy parameters are based on the values provided by the supplier, [6], that brings the current consumption of the sensor node MICA2. Besides that we work with instances of 4 time periods and a battery capacity that allows the nodes to be active for two periods.

3.2 Computational Results

The tests use the optimization commercial package CPLEX 7.0 [7]. The optimal solutions for instances with the sink node place in the center of the sensor field are in Table 1. The value of active nodes is the arithmetic mean of active nodes in each period. The value of coverage fail is the arithmetic mean of the fail (demand points not covered / total of demand points) in each period. The standard deviation regards the value of this mean.

The results for instances with the sink node in the bottom left corner of the sensor field are in Table 2. The results for instances with the sink node in the center of the sensor field and precision $n = 2$ are in Table 3. For these test we show the coverage fail as total coverage fail and parcial coverage fail. The first one represents the arithmetic mean of non covered demand points and the second the arithmetic mean of demand points covered for one sensor node. The demand points covered by only one node can be seen as areas whose sensing data are less precise, but that still can be used by the observer to infer environment features.

Comparing the results of Table 1 and Table 2 we notice that when we move the sink node to the sensor field corner the number of actives sensor nodes

Table 1. Optimal Solution for 1 sink node in the center

Communication Range (m)	Sensing Range (m)	Active Nodes	Standard Deviation (nodes)	Energy Consumption (mAh)	Coverage Fail (%)	Standard Deviation (coverage)
7.5	7.5	1.5	1.73	43.95	78.91	24.20
7.5	10	1.5	1.73	43.95	70.50	33.90
7.5	12.5	1.0	1.73	27.23	61.58	44.25
10	7.5	7.5	0.58	211.83	7.0	3.60
10	10	7.0	0.0	195.02	0.6	0.64
10	12.5	5.0	0.0	136.36	0.0	-
12.5	7.5	7.0	0.0	184.81	2.24	0.74
12.5	10	6.5	0.58	172.19	0.0	-
12.5	12.5	4	0.0	103.00	0.0	-

Table 2. Solution for 1 sink node in the corner

Communication Range (m)	Sensing Range (m)	Active Nodes	Standard Deviation (nodes)	Energy Consumption (mAh)	Coverage Fail (%)	Standard Deviation (coverage)
7.5	7.5	1.5	1.73	43.95	80.00	23.00
7.5	10	1.5	1.73	43.95	73.24	30.76
7.5	12.5	1.5	1.73	43.95	67.50	37.42
12.5	12.5	5.5	0.58	159.70	0.0	-

Table 3. Optimal Solution for precision $n = 2$

Communication Range (m)	Sensing Range (m)	Active Nodes	Total Coverage Fail (%)	Standard Deviation (total coverage)	Parcial Coverage Fail (%)	Standard Deviation (parcial coverage)
7.5	7.5	1.5	78.10	24.20	10.4	12.10
7.5	10	1.5	70.52	33.90	10.7	12.38
7.5	12.5	1.5	61.58	44.25	11.10	12.84
12.5	7.5	8	3.60	1.39	42.17	2.03
12.5	10	8	0.80	0.74	7.75	1.02
12.5	12.5	7	0.00	-	1.11	1.30

increase because the path to sink also increases. Table 3 shows that the greater the precision is, the more the actives nodes are.

The high coverage fail and standard deviation values for the communication range of 7.5m have two main causes: low network connectivity and battery capacity. The low network connectivity, due to the short communication range, allows the activation of few nodes because if there is no path between the source node and one of the active sink nodes this node remains inactive. Besides that, in all tests we use a battery capacity that allows all nodes to remain actives for two periods only.

The results show that the model is sensible to different sensing range values, the greater the range is, the less the actives nodes are. However, regarding the communication range this affirmation is not true, because the communication range assures the network connectivity and when this range is really short and the nodes cannot reach each other, they are not activated.

The model's main problem is its complexity, which requires a great computational effort to find the solutions and for some instances it is impossible to reach an optimal or even a feasible solution at reasonable time.

3.3 Energy Consumption

The energy savings with the node scheduling are evaluated comparing networks with and without node scheduling schemes. We assume that in the network without scheduling all nodes are active, and the model solutions provides the routes

Table 4. Energy consumption comparison

Period	With scheduling		Without scheduling	
	Active Nodes	Energy Consumption (mAh)	Active Nodes	Energy Consumption (mAh)
0	8	6137,283	16	12274,464
1	8	5961,283	16	11922,646
2	8	6137,181	16	11003,073
3	8	5961,181	0	0,000

for data dissemination. Table 4 presents the comparison between topologies with and without scheduling for an area of $3600m^2$, 16 sensor nodes, four sink nodes in the sensor field corners, communication range of 25m, sensing range of 15m, and grid positioning. As we can note, without scheduling there is no active node after the third period. Although the node scheduling can causes coverage fail, it allows network activities during all time periods, because the solution can schedule nodes in all periods assuring the best possible coverage.

4 Related Works

Megerian et al. [8] propose several ILPs models to solve the coverage problem. Their focus is the energy efficient operation strategies for WSN. This approach is similar to ours, except that it defines areas sets that should be covered instead of demand points, and the work does not deal with dynamic problems.

Chakrabarty et al. in [9] present a Integer Linear Programming (ILP) Model that minimizes the cost of heterogenous sensor nodes, and guarantees sensor field coverage. Their problem is defined as the placement of sensor nodes on grid points, and they propose two approaches: a minimum-cost sensor placement, and a sensor placement for target location.

The dynamic multi-product problem of facilities location is formulated for Hinojosa, Puerto, and Fernández in [10] in a mixed integer linear programming model. In this work the objective is to minimize the total cost to demand attendance of the products in a planning horizon and also assure that the producers and intermediate deposits capacities are not exceeded. The problem lower bound is obtained by Lagrangian Relaxation. With this solution a heuristic is used to obtain feasible solutions.

5 Conclusion

This work presents a dynamic mixed integer linear programming (MILP) model to solve the coverage and connectivity dynamic problem(CCDP) in flat WSNs. The model optimal solution indicates the set of sensor nodes that should be actives to guarantee the sensor field coverage and a path between each active sensor node and a sink node for each time period. The solution is chosen in order to minimize the network energy consumption.

In general we can conclude that the dynamic planning as proposed save energy compared with a network without node scheduling and also assure activity during all periods. The model provides a route between the source nodes, and the sink node, and different routing protocols can be used over the topology provided for the model solution.

Future work includes the development of algorithms and heuristics to solve bigger problems and to decrease the solution time because the model complexity requires a great computational effort and sometimes it is impossible to reach an optimal solution in reasonable time. The first chosen technique is Lagrangian Relaxation [11].

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