

**MULTI-OBJECTIVE OPTIMIZATION
WITH QoS CONSTRAINTS IN WSNs**

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Abstract

One of the most active research areas in wireless sensor networks are coverage and improving QoS parameters. This paper focuses on the deployment optimization problem of WSNs dedicated to the monitoring area of interest. In this kind of networks, nodes are classified into two classes: Sensor Nodes (SNs) deployed within the area of interest for targets coverage and Relay Nodes (RNs) which relay sensed messages generated by the sensor nodes up to the sink node. In this study, we propose a Multi-Objective Throughput and Lifetime Optimization (MOThLO) which maximizes simultaneously the throughput and lifetime of sensor nodes, while ensuring network energy, latency and sensors lifetime. In order to evaluate the performance of our proposal, we have conducted many tests.

Key words: sensor nodes, wireless sensor networks, QoS constraints, throughput, multi-objective combinatorial optimization

2020 Mathematics Subject Classification: 68M07, 68M12, 68M18, 90C29

Introduction. Wireless sensor networks are very attractive because these networks enable promising applications, but there are many system challenges to resolve [1] like the limited communication throughput of the sensors, energy, which is an essential problem since sensors are usually battery-powered, and in some emergency applications, a short time of data collection is also required.

To satisfy the above requirements, TDMA is a good choice towards such a data gathering sensor networks. Saving energy is done by eliminating collisions, avoiding idle listening, entering inactive states where other sensors transmit packets, bounding the delays of packets which is important for the time-driven data aggregation [2], and guaranteeing reliable communication, which is maintained by TDMA protocol, as a collision-free access method.

In Tree based Data Aggregation Techniques, nodes are organized in a tree topology, as clusters [3,4], where the sink node is represented as a root. All the intermediate nodes perform the aggregation and transfer it to the root. Energy efficient tree construction is the main aspect in the tree based approach [5].

The lifetime of a sensor network has numerous distinctive definitions. However, there has to be a definition which is most palatable and suitable to embrace. The lifetime of a sensor network is most commonly characterized as the time from the moment the network begins working to the primary sensor node disappointment [6].

Energy consumption increases due to several reasons such as unsuccessful delivery of packets to the receiver, re-transmission of packets, delay in packet delivery to the sink, low received signal strength, inadequate link quality, noise level, etc [7].

In WSN, transmitted sensed data from the nodes to sink may run through many paths. The available bandwidth in the network (channel) will be portioned, and the response times will become overlong [8]. The real time applications of wireless sensor networks are bandwidth sensitive and need higher share of bandwidth to respond to the dead-line requirements.

Related works. In the following, we review some works related to the increasing lifetime and throughput problem of WSNs.

HANH et al. [9] focus on minimizing the number of nodes (i.e., sensor nodes and relay nodes) while ensuring target coverage, connectivity and fault tolerance in wireless sensor networks. They divide this problem into two sub-problems. Target Coverage, which requires placing sensor nodes to cover all targets, and Network Connectivity and Fault Tolerance, in which relay nodes need to be placed to connect sensor nodes to the base station, along with a backup path in case of failure.

In order to achieve the global optimality of minimum-cost heterogeneous node placement, SUN and HALGAMUGE [10] find the locations of base stations, sensor nodes, and relay nodes, simultaneously. Minimizing the sum of node production and placement costs and transmission outage probabilities in the routing tree is the objective of their study.

Coverage gets to be one of the foremost critical challenges of WSNs. Seeking for superior positions to assign to the sensors in arrangement to control each placement in the zone of interest and the collection of information from sensors are major preoccupations in WSNs. The work of NJOYA et al. [11] addresses these

notions by providing a hybrid approach while ensuring sensors deployment on a grid for targets coverage by taking into account connectivity.

To review some works published on multi-objective optimization algorithms applied in wireless sensor networks field and to achieve various trade-offs among different conflicting objectives, IQBAL et al. [12] summarize different objectives used to formulate the multi-objective optimization problem, i.e., maximization of coverage, minimization of packet error rate, maximization of network life, maximization of energy efficiency, minimization of cost, minimization of delay and maximization of throughput.

In our previous work [13], and in order to assign the maximum bandwidth to all sensor nodes, three solutions are presented in detail: Spiral-Based Clustered Data Aggregation (SBCDA) architecture, Tree-Based Clustered Data Aggregation (TBCDA), and Tree-Based Clustered Wireless Sensor Network (TBC-WSN). Aggregating data can reduce the number of the packets transmitted to the sink, where each cluster head (CH) collects and aggregates received packets from its child nodes, before transmitting the resulting packet to its parent, until the data reaches the sink node (base station).

Network description and assumptions. As depicted in Fig. 1, we consider a WSN consisting of many homogeneous sensor nodes and a sink node. We consider that our network works without inter or intra-cluster interference, and all sensor nodes are similar and sense the same events (temperature for example). We adopt a perfect data aggregation model and TDMA-based scheduling protocol. This network is characterized by:

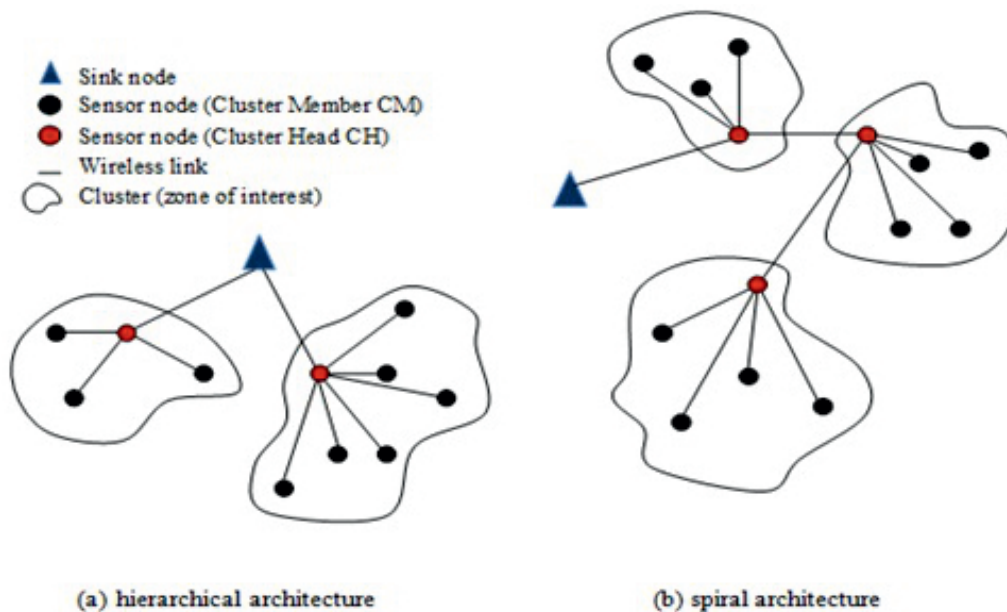


Fig. 1. Example of sensors architecture deployment in WSN

- Network type: we assume that our network architecture is both hierarchical “tree-based” and “spiral-based”.
- Synchronization of sensors: The time synchronization of the network can be carried out by applying a synchronization algorithm, or by sending a signal from the sinks or other entity capable of reaching all sensors.

Problem formulation. Our area of interest is discrete (surveillance zone), where we obtain a set of zones. All sensors cover all zone targets distributed inside the area of interest, which we want to monitor by SNs. Each sensor is characterized by a sensing range R_s , assumed to be constant. SNs (sensor nodes) and RNs (relay nodes) can be placed randomly in this zone. All sensors cover the targets if their sensing range completely covers the targets. In other words, if the Euclidean distance between each sensor and the target covered is no more than R_s . Targets covered in this network are classified as clusters which regroup certain number of sensors managed by one sensor named *Cluster Head (CH)*.

We consider the problem as a graph consisting of the sets of N sensor nodes SN and one sink. Each sensor $x_{i,j}^h$ has a list of child sensors that can transmit their packets. The objectives are to maximize:

- The throughput of each sensor node in the network;
- The lifetime of sensors including the network itself;

under the following constraints:

- Every cluster in the network must be connected to another by at least one sensor node which will be a child node in one cluster and a cluster head in another.
- Every sensor not neighbour of the sink must be connected to the sink node using at least one path composed of SNs.
- Packets transmissions are free of inter and intra cluster interferences.

Optimization problem. In this section, we first give some definitions. Then, we present the proposed approach, and describe the resolution method and how to deal with the objectives.

A. Definitions. Table 1 summarizes all of our model’s related parameters and variables.

B. Proposed multi-objective model. Using the above parameters and decision variables, the proposed model can be written as follows:

$$(1) \quad \text{Max} \sum_{h=1}^N Th_{x_{i,j}^h},$$

T a b l e 1
Parameters and variables

Parameter	Definitions
$Th_{x_{i,j}^h}$	Throughput of sensor node $x_{i,j}^h$
Lt_{x^h}	Lifetime of sensor node $x_{i,j}^h$
$x_{i,j}^h$	$\bigcup_h (\text{SN}, \text{RN})$ Sensor node $x_{i,j}^h$ at level i of cluster j
$x_{i+2k,j}^h$	Sensor node $x_{i+2k,j}^h$ at level $i + 2k$ of cluster j (all sensor nodes of even levels)
$\text{Send}_{x_{i,j}^h}$	$= \begin{cases} 1 & \text{if } x_{i,j}^h \text{ is in active mode} \\ 0 & \text{if } x_{i,j}^h \text{ is in sleep mode} \end{cases}$ Variable that determine if a sensor $x_{i,j}^h$ is in active (send/receive) or sleep mode
N	Number of sensors
B	Bandwidth reserved for the network
e_h	$e_h = \sum_{i=1}^f \sum_{j=1}^{f'} x_{i,j}^h (E_{tx} + E_{rx})$ Amount of energy for sensor $x_{i,j}^h$
E	Energy of the network
Rt^h	Response time (latency) of sensor $x_{i,j}^h$
S	Superframe length
Ts	Time slot (duration of packet transmission)
C_i^j	Cluster j at level i

$$(2) \quad \text{Max} \sum_{h=1}^N Lt_{x^h}$$

subject to:

$$(3) \quad \sum_{h=1}^N \text{Send}_{x_{i,j}^h} = 1,$$

$$(4) \quad \sum_{j=1}^d \sum_{h=1}^N \sum_{k=1}^m \text{Send}_{x_{i+2k,j}^h} < N \text{ for all } d \leq f', h, k,$$

$$(5) \quad \sum_{h=1}^N Th_{x_{i,j}^h} \leq B,$$

$$(6) \quad \sum_{l=1}^m T_l x_{i,j}^h \leq m + 1,$$

$$(7) \quad \sum_{h=1}^N x_{i,j}^h (E_{tx} + E_{rx}) \leq e_h,$$

$$\begin{aligned}
(8) \quad & \sum_{h=1}^N E_{tx_{x^h}} + \sum_{h=1}^N E_{rx_{x^h}} \leq E, \\
(9) \quad & e_h \leq E, \\
(10) \quad & Rt^h < S + t, \\
(11) \quad & Lt_{x^h} = (e_h * S) \left/ \left(\sum_{h=1}^N E_{tx_{x^h}} + \sum_{h=1}^N E_{rx_{x^h}} \right) \right., \\
(12) \quad & S = \sum Ts, \\
(13) \quad & x_{i,j}^h \in C_i^j, \quad h = 1, \dots, N, \quad i = 1, \dots, f, \quad j = 1, \dots, f'.
\end{aligned}$$

The objective is to maximize simultaneously, the throughput allocated to sensor nodes $x_{i,j}^h$, of level i , and cluster j , in a mentioned architecture, and their lifetime.

Constraint (3) ensures that just one sensor node in cluster j at level i is allowed to transmit its packets in order to avoid intra-cluster interferences. Constraint (4) ensures that simultaneous transmissions are allowed just for sensors in clusters j ($j = 1, \dots, f'$) at even levels $i + 2k$ to transmit their packets in order to avoid inter-clusters interferences. Constraint (5) guarantees that the total available network bandwidth is greater than or equal to the sum of allocated throughputs for all sensors. To determine the number of packets to transmit, constraint (6) defines the sum of possible transmissions T_l , of a sensor node $x_{i,j}^h$, of level i , cluster j , having m descendants (child and their child nodes), is at most equal to $m + 1$ packets. Constraint (7) shows that no sensor node can expend more than its battery energy (e_h). The energy consumption of all the sensors in the network cannot spend the total energy of the network which is described in constraint (8).

The amount of energy for a sensor to receive a packet is denoted by E_{rx} and the amount of energy for a sensor to transmit a packet is denoted by E_{tx} . The energy consumption for transmitting and receiving data is assumed to be the dominant factor in the energy consumption of each sensor node. Energy consumption for processing data is assumed to be negligible compared with that for transmitting and receiving data. Each sensor is battery operated. In contrast, the sink node is assumed to be energy abundant [18]. Generally, $E_{rx} < E_{tx}$. Typical settings of $E_{rx}:E_{tx}$ are 1:2.5 [14], 1:3 [16], 1:3.2 [17], and 1:4.2 [15], etc.

With constraint (9), the energy of each sensor node is at most equal to the total energy of the network E .

Network latency is the amount of time it takes for a packet to cross the network from a sensor node to the destination (sink node). The delay could be considered a synonym for latency. Latency and throughput define the speed and capacity of a network. Constraint (10) ensures that the latency time (Response

time) of the node $x_{i,j}^h$ is the minimum possible, where S is the superframe and t is the beginning time of network operation.

We define sensor lifetime in constraint (11) as according of its own energy, the size of the superframe and the energy of sending and receiving (packets transmission and reception).

The superframe length is the duration of a round (cycle) where all sensors send their data, i.e. from leaf nodes (at last level $\#f$) to first level's nodes and to the sink. This is represented as the sum of all time slots reserved for sensor nodes in the network according to constraint (12).

Constraint (13) describes how each sensor node is defined as either a cluster member or a cluster head in a cluster.

Simulation results. In order to validate our work, we have conducted some simulations to evaluate the performance of the proposed model.

To produce the set of effective solutions, we choose the ε -constraint approach. This method consists in transforming the multi-objective problem to a mono-objective problem by considering one objective to optimize among the others and making the remaining objectives as bounded constraints. We solve the linear program iteratively, where we maximize the objective function (1) while the objective function (2) is considered constraint delimited by ε_{f2} . At each iteration, we increase the bound ε_{f2} to obtain a new solution.

Our mathematical model is solved using ε -Constraint approach and executed on a PC with a two-core Intel Core Processor (2.40 GHz) and 16 GB RAM.

In order to interpret the results, and as an example, we have arbitrarily taken the consumptions (consumed energy) for each state as follows:

- Transmission: 37.5 mW with Idle state: 22.5 mW and Sleep state: 0.1 mW.
- Reception: 34 mW with Listening state: 22.5 mW and Sleep state: 0.1 mW.

Simulation parameters are described as follows:

- Packets size: 30 Bytes
- Simulation duration: Up to 7000 s
- MAC Layer: TDMA
- Channel bit rate: 260 Kbs
- Length of time slot: 100 ms
- Initial energy of each node: 6 AA battery, 2.85 Ah

Figure 2 shows that the time to first node failure (leaf node) exceeds the time to CH node failure (CH with 9 child nodes).

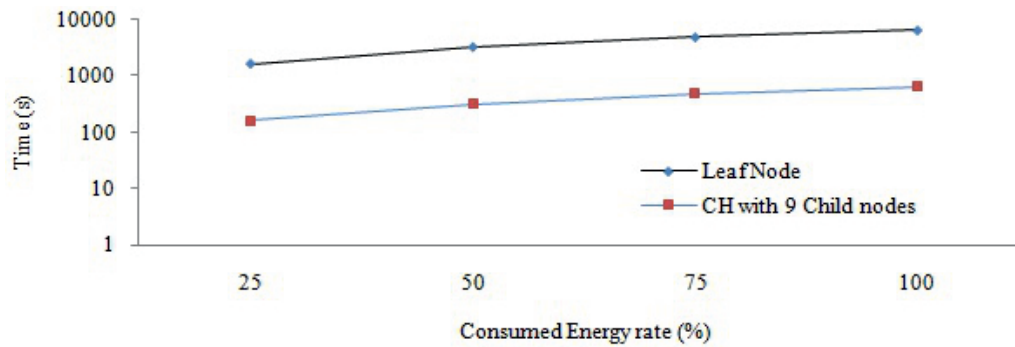


Fig. 2. Time elapsed before the failure of leaf node and CH with 9 child nodes according to the rate of energy consumed

Each sensor node transmits sensed and received packets, where a leaf node (nodes without children) transmits just sensed data, and this is why their lifetime is greater than CHs in the network (except where a sensor fails). This means that the sensors consume their energies differently, and if these sensors are dispersed randomly, we do not know which of them will fail first.

To avoid this problem, where sensors are randomly dispersed, and to extend the lifetime of the network, we have to place nodes, with high level of energy, at highest levels in the network (our model manages sensors extremely placed statically).

In Fig. 3, we found out throughput analysis for sensor network having 50, 100, 150 and 200 nodes. Throughput graph was plotted with respect to time period. We observed from the graph that throughput increased gradually and reached a height of 252 kbps.

Figure 3 presents a graph of throughput (kbps) vs. network density. The density is varied from 50 to 200 sensor nodes. It is observed that up to 50 sensors

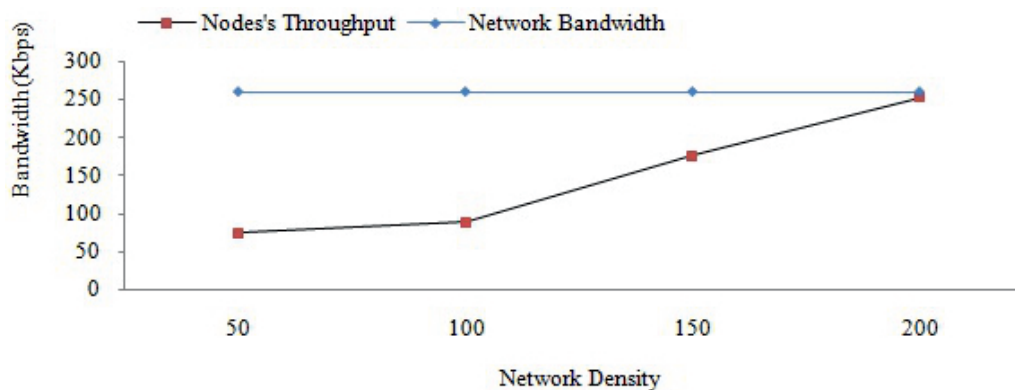


Fig. 3. Throughput vs. network density

the graph is increasing to 75 kbps, and then it reaches 90 kbps with 100 nodes, and after that the graph evolves linearly until reaching the maximum throughput (network bandwidth).

Conclusion. In this paper we study the problem of multi-objective optimization with network energy, latency and lifetime constraints in wireless sensor networks.

Due to slot reuse and in some protocols, TDMA, which has a natural advantage of collision-free medium access, leads to interference. Adaptation to topology changes is another difficulty faced by TDMA system as these changes are caused by exhaustion of battery capacities for example in decentralized environment; it is not easy to change the slot assignment for traditional TDMA.

Moreover, the proposed approach provides a faster data delivery to the cluster head (CH) using TDMA scheme that is very important for real time applications.

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