Paper

A Survey of Multi-Objective Deployment in Wireless Sensor Networks

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Abstract—The major challenge in designing wireless sensor networks (WSNs) is to find tradeoff between the desired and contrary requirements for the lifetime, coverage or cost while coping with the computation, energy and communication constraints. This paper examines the optimal placement of nodes for a WSN. It is impossible to consider the deployment of the nodes separately from WSNs applications. We highlight the properties of WSNs applications that determine the placement problem. We identify and enumerate the various objectives that should be considered. The paper provides an overview and concentrates on multi-objective strategies, their assumptions, optimization problem formulation and results.

Keywords—coverage, lifetime, placement, positioning, wireless sensor network.

1. Introduction

In recent years, with advance in wireless communication technology, sensing technology, micro-electronics technology and embedded system, wireless sensor networks can be used for a wide variety of applications and systems with vastly varying requirements and characteristics, such as environmental monitoring, disaster management, factory automation, health care or military. Typical sensor network consists of a large number of spatially distributed autonomous sensor devices. Nodes networked through wireless must gather local data and communicate with other nodes.

A wireless sensor network (WSN) design is influenced by many factors such as transmission errors, network topology and power consumption. Consequently, developing a WSN application introduces several implementation challenges. This paper describes one of the most fundamental issue in WSN designing – the deployment problem. This specific problem has different appellations in the literature, e.g., placement, layout, coverage or positioning problem in WSNs. The term positioning seems to be more general, so we propose a taxonomy illustrated in Fig. 1. On the left is localization – its aim is to locate where the nodes are placed. On the right is deployment (placement) – its aim is to determine where the nodes should be placed. In the vast majority of deployment problems the coverage is considered, but this is not necessary and depends on the application. More details about the applications and its properties can be found in Section 2.

In this paper we concentrate on optimal node placement. This is one of the most important design step to selectively decide the locations of the sensors to optimize the desirable objectives, e.g., maximize the covered area or minimize the energy use. Fundamental questions in this case include [1]:

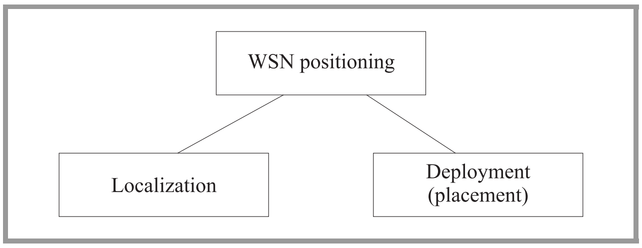

Fig. 1. A taxonomy for positioning in WSN.

- How many sensor nodes are needed to meet the overall system objectives?
- For a given network with a certain number of sensor nodes, how do we precisely deploy these nodes in order to optimize network performance?
- When data sources change or some part of the network malfunctions, how do we adjust the network topology and sensor deployment?

2. Wireless Sensor Network Applications and Properties

In the past, a number of early, mostly US-based research projects established a de facto definition of a wireless sensor network as a large-scale, wireless, ad hoc, multi-hop, unpartitioned network of largely homogenous, tiny, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in the area of interest [2].

More recently WSNs are used in a huge variety of scenarios. Such diversity translates into different requirements and the above definition of a wireless sensor network does not necessarily apply for those scenarios. The knowledge about sensor networks is evolving in many different directions. Of course we still have a classical sensor networks but now we can also distinguish a mobile sensor networks [3], wireless sensor and actuator networks [4], wireless multimedia sensor networks [5] and many others. This coarse-grained division cannot be treated as a classification of sensor networks. It illustrates only some emerging trends which enhances diversity in WSNs. In many applications a network is small-scale with a few dozens of nodes, some nodes are mobile, they are not homogeneous etc. This diversity can be considered in many different dimensions. Römer and Mattern [2] propose over ten properties characterizing existing WSN applications such as size, mobility, heterogeneity, communication modality etc. Another taxonomy can be found in Mottola and Picco survey [6], illustrated in Fig. 2.

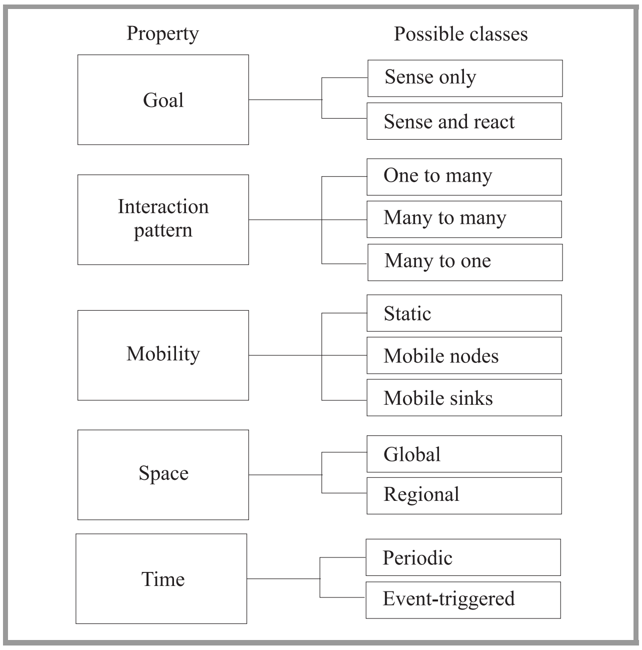

Fig. 2. A taxonomy of WSN applications by [6].

Goal. In the majority of WSNs applications, especially the early ones, the goal is to gather environmental data for later analysis (*sense-only*). This can be done by a field of sensor-equipped nodes which sends their data, possibly along multiple hops, to a single base station that centrally collects the readings. However now we can distinguish also applications where some WSN nodes are equipped with actuators. In WSANs, the roles of sensor and actor nodes are to collect data from the environment and perform appropriate actions based on this collected data, respectively *sense and react* [4].

Interaction pattern. Another key property is interaction pattern between the network nodes – the way how the network nodes exchange information with each other, which is somehow affected also by the application goal they are trying to accomplish. The most popular interaction pattern is *many-to-one*, where data is send from all nodes in the network to a central collection point. Nevertheless, *one-to-many* and *many-to-many* interactions can also be found. The former are important when it is necessary to send configuration commands (e.g., a change in the sampling frequency or in the set of sensors active) to the nodes in the network. The latter is typical of scenarios where multiple data sinks are present, a situation often manifest in sense-and-react scenarios.

Mobility. This is probably the most noticeable property. Sensor nodes may change their location after initial deployment. Mobility may apply to all nodes within a network or only to subsets of nodes. Mottola and Picco [6] distinguish three classes *static*, *mobile nodes* and *mobile sinks*. Roughly the same classes are described in [2], but Römer indicates also some other aspects of mobility – shown in Fig. 3. Mobility can result from environmental influences such as wind or water, sensor nodes may be attached to or carried by mobile entities – *passive mobility*. Sensor nodes may possess automotive capabilities – *active mobility*. The degree of mobility may also vary from *occasional* movement with long periods of immobility in between, to *constant* travel.

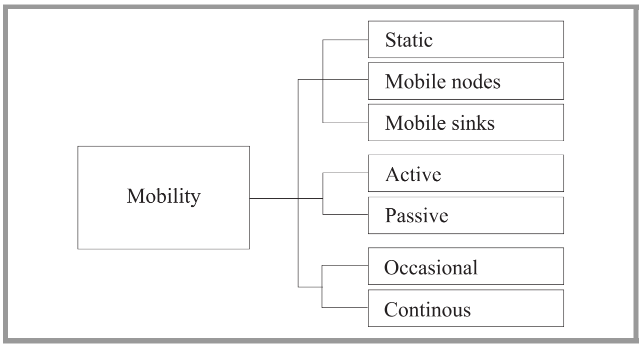

Fig. 3. Extended mobility taxonomy.

Space. Different applications may require the distributed processing spreading different portions of the physical space. The space can be *global* where the processing involves in principle the whole network, most likely because the phenomena of interest span the whole geographical area where the WSN is deployed or *regional* where the majority of the processing occurs only within some limited area of interest.

Time. In WSNs usually the term *time* is associated with the network lifetime, which has a high impact on the required degree of communication and energy efficiency. However the term time can also characterize the way how the distributed processing is done. If the network is used to monitor some considered area, the application can perform *periodic* tasks to gather sensor readings. This solution is maybe not energy efficient, but collected data may be used in further analysis. Another way to monitor the same area is *event-triggered* solution – the application is characterized by two phases:

- during event detection, the system is largely quiescent, with each node monitoring the values it samples from the environment with little or no communication involved;
- if and when the event condition is met (e.g., a sensor value raises above a threshold), the WSN begins its distributed processing [6].

Obviously the provided classification is not complete. It is certainly debatable which issues are important enough to be explicitly listed and one could argue in favor of adding more dimensions. In order to categorize the various strategies for nodes positioning it is worth considering to add two more properties: *heterogeneity* and *network topology*.

Heterogeneity. Early sensor network visions anticipated that sensor networks would typically consist of homogeneous devices that were mostly identical from a hardware and software point of view [2]. However, in many applications available today, sensor networks consist of a variety of different devices. Nodes may differ in the type and number of attached sensors; some nodes may act as gateways to long-range data communication networks (e.g., GSM networks or satellite networks). The differences between nodes can be also connected with roles the nodes play in the network (some nodes my work as a cluster heads). The roles assignment can be temporary or permanent.

Network topology. Another important property of a sensor network is the maximum number of hops between any two nodes in the network. In its simplest form, a sensor network forms a single-hop network, with every sensor node being able to directly communicate with every other node or the base-station at least. In multi-hop networks nodes may forward messages over multiple hops.

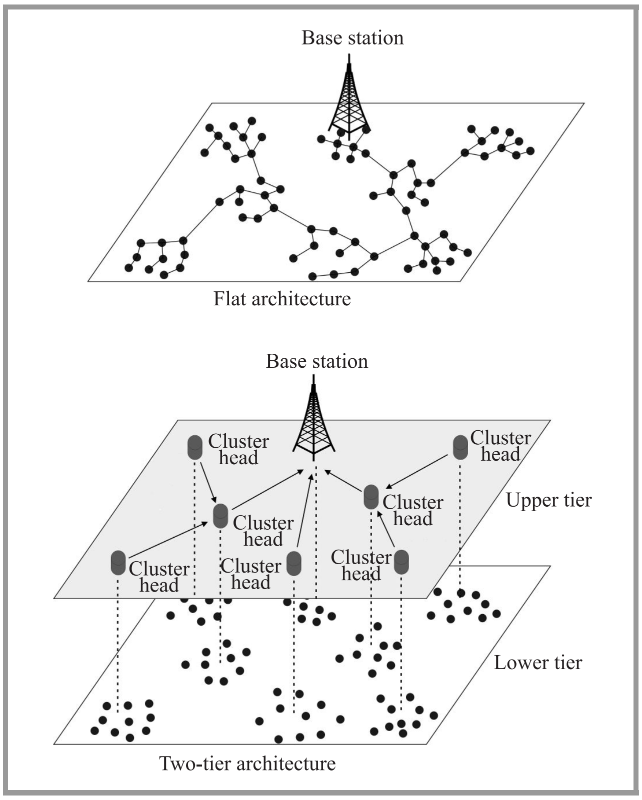

Fig. 4. Flat and tiered network topologies.

The sensor network architecture can be flat where all sensors play the same role in communication – all nodes acts as routers or it can be tired. The most common is two-tier where sensors are split into clusters; each is led by an cluster head node, as illustrated in Fig. 4.

3. Objectives

The positioning of nodes in a sensor network has received a notable attention in research. The localization and deployment are the fundamental issues and the number of papers concerning these problems exceeds few hundred. Good overview of various strategies for node placement has been provided by Younis and Akkaya [7]. They have distinguished four primary objectives for sensor deployment, such as: area coverage, network connectivity, network longevity and data fidelity. In this section we extend the list and provide a short overview of optimization objectives.

3.1. Coverage

The coverage problem is the objective that has been widely discussed in the literature. Typically considered problems are area coverage, point/target coverage, energy-efficient coverage and *k*-coverage problem. Assessing the coverage varies based on the underlying model of each sensor's field of view and the metric used to measure the collective coverage of deployed sensors.

The most commonly used sensor coverage model is a sensing disk model. All points within a disk centered at sensor are considered to be covered by the sensor. In the literature of WSNs, however, many papers assume a fixed sensing range and an isotropic detection capability of sensor. The detection ability within coverage of a sensor can be classified as the 0/1 coverage model (binary model), the probabilistic coverage model, and the information coverage model. Some of the published papers, especially early ones, use the ratio of the covered area to the size of the overall deployment region as a metric for the quality of coverage. Since 2001, however, most work has focused on the worst case coverage, usually referred to as least exposure, measuring the probability that a target would travel across an area or an event would happen without being detected [7].

3.2. Differentiated Detection Levels

Differentiated sensor network deployment, which considers the satisfaction of detection levels in different geographical characteristics, is also an important issue. In many realworld WSN applications, such as underwater sensor deployment or surveillance applications, the supervised area may require extremely high detection probabilities at certain sensitive areas. However, for some not so sensitive areas, relatively low detection probabilities are required to reduce the number of sensors deployed so as to decrease the cost. In this case, different areas require different densities of deployed nodes Therefore, the sensing requirements are not uniformly distributed within the area. As a result, the deployment strategy of WSN should take into consideration the geographical characteristics of the monitored events [8].

3.3. Network Connectivity

Another issue in WSN design is the connectivity of the network. We say that the network is connected if any active node can communicate with any other active node (possibly using other nodes as relays). Network connectivity is necessary to ensure that messages are propagated to the appropriate base station and the loss of connectivity if often treated as the end of network life. This property is strongly connected with coverage and energy efficiency (the value of transmission range may vary according to transmission power). The relationship between coverage and connectivity results from sensing and transmission ranges. If the transmission range of a node is much longer than its sensing range then connectivity is not an issue, because the coverage ensures there is a way to communicate. Situation is different if the communication range is less than sensing range.

3.4. Network Lifetime

One of the major challenges in the design of WSNs is the fact that energy resources are very limited. Recharging or replacing the battery of the sensors in the network may be difficult or impossible, causing severe limitations in the communication and processing time between all sensors in the network. Note that failure of regular sensors may not harm the overall functioning of a WSN, since neighboring sensors can take over, provided that their density is high. Therefore, the key parameter to optimize for is network lifetime – the time until the network gets partitioned in a way that is is impossible to collect the data from a part of the network [9].

3.5. Data Fidelity

Ensuring the credibility of the gathered data is obviously an important design goal of WSNs. A sensor network basically provides a collective assessment of the detected phenomena by fusing the readings of multiple independent (and sometimes heterogeneous) sensors. Data fusion boosts the fidelity of the reported incidents by lowering the probability of false alarms and of missing a detectable object. Increasing the number of sensors reporting in a particular region will surely boost the accuracy of the fused data. However, redundancy in coverage would require an increased node density, which can be undesirable due to increased *cost* or decreased *survivability* (the potential of detecting the sensors in a combat field) [7].

3.6. Energy Efficiency

This criteria is often used interchangeably with *lifetime*. Due to the limited energy resource in each sensor node, we need to utilize the sensors in an efficient manner so as to increase the lifetime of the network. There are at least two approaches to the problem of conserving energy in sensor networks connected with optimal placement. The first approach is to plan a schedule of active sensors that enables other sensors to go into a sleep mode utilizing overlaps among sensing ranges. The second approach is adjusting the sensing range of sensors for energy conservation.

3.7. Number of Nodes

This criteria is obvious. The more sensors are used the higher is cost. At least the half of the papers dedicated to optimal node deployment consider to achieve the specified goals with minimum cost.

3.8. Fault Tolerance and Load Balancing

Fault tolerant design is required to prevent individual failures from shortening network lifetime. Many authors focus on forming k-connected WSNs. K-connectivity implies that there are k independent paths among every pair of nodes. For $k >= 2$, the network can tolerate some node and link failures. Due to many-to-one interaction pattern k-connectivity is especially important design factor in the neighborhood of base stations and guarantee certain communication capacity among nodes.

4. Multi-Objective Approaches

The criteria presented in previous section are conflicting objectives (e.g., coverage versus energy consumption, fault tolerance vs survivability). Thus, there is no single nodes placement that can optimize all objectives simultaneously and a decision maker needs an optimal trade-off. In this section we provide an overview of published work according to multi-objective methods for nodes placement in wireless sensor networks. Table 1 consist the list of papers with considered objectives.

All the works except paper [10] treat a coverage as one of the objectives. Molina *et al.* have also considered coverage but as a constraint. Their aim is to obtain a full coverage network with minimum cost and maximum lifetime. The lifetime is defined as the time until the first node fails (time to first failure – TTFF). The terrain is modeled as a discrete grid, where each point in the grid represents one square meter of the terrain. They assume a nonfixed amount of homogeneous sensor nodes has to be placed in the terrain. The number of sensor nodes and their locations have to be chosen in a way that minimizes the energy spent in communications by the most loaded node in the network and the cost of the network which, in this case, is calculated as the number of deployed sensor nodes. All presented algorithm was able to find a front of non-dominated feasible solutions. Authors do not provide any model of preferences and do not select the preferred solution.

Another paper with discretized space – this time in 3D – have been written by Kang and Chen. In paper [11] N sensors are deployed to cover the sensor field. The sensor field consist of $k \times k \times k$ grid points in the x, y, z dimensions. Each sensor has an initial sensor energy and has the capability to adjust its sensor range. Sensing range options correspond to energy consumptions and detection error ranges. Three objectives are considered: maximization of coverage,

Table 1
A comparison between the various approaches for multi-objective nodes placement

No.	Title	Objective 1	Objective 2	Objective 3
1	An evolutionary approach for multi-objective 3D differentiated sensor network deployment [11]	Coverage	Differentiated detection levels	Energy efficiency
2	Layout optimization for a wireless sensor network using a multi-objective genetic algorithm [12]	Coverage	Lifetime	
3	Adaptive design optimization of wireless sensor networks using genetic algorithms [9]	Energy-related parameters	Sensing points' uniformity	
4	Multi-objective optimization for coverage control in wireless sensor network with adjustable sensing radius [13]	Coverage	Number of sensors	Energy efficiency
5	Energy efficient coverage control in wireless sensor networks based on multi-objective genetic algorithm [14]	Coverage	Number of sensors	
6	Optimal sensor network layout using multi-objective metaheuristics [10]	Energy efficiency	Number of sensors	
7	A multi-objective evolutionary algorithm for the deployment and power assignment problem in wireless sensor networks [15]	Coverage	Lifetime	
8	Multi-objective genetic algorithm for the automated planning of a wireless sensor network to monitor a critical facility [16]	Coverage	Survivability	Number of sensors

Table 2
A properties of the various approaches for multi-objective nodes placement

No.	Number of sensors	Initial deployment	Time	Heterogeneity	Network topology
1	Constant	Controlled	Event-triggered	Homogeneous	Flat
2	Constant	Controlled	Periodic	Homogeneous	Flat
3	Constant	Controlled	Periodic	Homogeneous	Two-tier
4	Variable	Existing	Periodic	Heterogeneous	Two-tier
5	Variable	Existing	Periodic	Heterogeneous	Two-tier
6	Variable	Controlled	Periodic	Homogeneous	Flat
7	Constant	Controlled	Periodic	Homogeneous	Flat
8	Variable	Controlled	Event-triggered	Homogeneous	Flat

maximization of differentiated detection levels and minimization of energy consumption. Decision variables are the 3D coordinates and the sensing ranges of all the nodes. As a final result authors present the box plots of obtained non-dominated solutions and the maximum and minimum objective values calculated in different objective functions. In paper there is no preference modeling.

Ferentinos *et al.* [9] have studied node positioning in a two-tiered network model. They concentrate on fulfilling some application specific objectives (from the scope of precision agriculture). The optimization problem is defined by the minimization of the energy-related parameters (operational energy, communication energy and battery capacity penalty) and the maximization of sensing points' uniformity, subject to the connectivity constraints and the spatial density requirement. The authors consider a cluster-based network architecture and a constant number on nodes. Unfortunately the provided solution cannot be treated as a multi-objective one, because all objectives was combined into single objective function (weighted sum approach).

Two-tiered architecture have been also considered by Jia *et al.* in papers [14] and [13]. The former paper is dedicated to optimal coverage control scheme in existing network. There are two objectives: maximization of coverage and minimization of number of sensors. In the paper [13], the problem of maintaining sensing coverage by keeping a small number of active sensor nodes and a small amount of energy consumption is studied. This time the list of objectives has been extended to include energy efficiency. Both papers show an interesting studies of multi-objective optimization. However Jia *et al.* consider slightly different task, because they optimize an existing network, so the nodes placement cannot be treated as decision variable. More information about differences in network properties for considered papers can be found in Table 2.

Typical trade-off between area coverage and network lifetime has been considered in papers [12], [15]. In both papers the considered area is a flat square surface where sensor nodes can monitor anything within R_{sensor}, and where they can communicate with any other node located within R_{comm}. In paper [12] the base station, with which every sensor must communicate (either directly or via hops through nearby sensors), is placed in the center of the area. Each sensor initially has the same energy available in its battery, and it is assumed that energy decreases by one arbitrary unit for every data transmission. The design variables are the 2D coordinates of the sensors. In paper [15] there is one additional vector of decision variables connected with the transmission power level of each sensor. Two objectives are considered: maximization of coverage and maximization of lifetime. As a final result authors present a Pareto front from which the user can choose.

Similar assumption about network configuration has been assumed in paper [16]. The sensors are identical and are placed in a flat square. The design variables are the 2D coordinates of the sensors. Three examples has been described by Jourdan and de Weck. The most interesting is monitoring movements in and aut of a facility served by two roads. The first objective is the coverage, by which is meant the ability of the network to monitor movements in and out of the facility. The second objective is the survivability of the network, by which is meant the likelihood that sensors will not be found. Each point in the area is assigned a probability of detection. This probability depends on the proximity of the facility or the roads. It is assumed that if a sensor is placed close to a road (where most of the activity takes place) or to the facility, it is more likely to be found and disabled. The third objective is the number of sensors. As a final result authors present a set of non-dominated solutions.

5. Summary and Conclusions

In this paper we outline the main properties and criteria that should be considered while deploying the nodes in considered area. We provided an overview of multi-objective strategies, their assumptions, optimization problem formulation and results. All the authors concentrate on optimization methods and finding a Pareto frontier. The model of preferences was not present in any paper and authors did not try to select the preferred solution. More work is required in order to provide the solution which can be applied in real applications.

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