Power Efficient Target Coverage in Wireless Sensor Networks

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1. Introduction

A Wireless Sensor Network (WSN) can be used in a variety of applications, such as in environmental monitoring and in battlefield surveillance in military applications (Akyildiz et al., 2002). A WSN consists of hundreds or thousands of sensors and, depending on the application, the node deployment and placement can be realised either in a deterministic way or randomly. In hostile environments, for example, sensors may be dropped from an aeroplane, resulting in a random placement, where the likely node density requirements cannot be guaranteed; some areas may contain more sensors than others.
Each sensor can collect data by monitoring a usually small area that it is in its sensing range. We say that the sensor provides *coverage* to this area. A sensor collects data periodically or continuously depending on the nature of the application and forwards the data to a node called the Base Station (BS) or sink which provides the necessary connections to infrastructure networking. A sensor node is equipped with a radio device that supports *connectivity* between two nodes or between a node and the BS.
One of the fundamental problems in WSNs is the coverage of the targets in conjunction with energy efficiency constraints. The problem of coverage in wireless sensor networks has been studied from many different aspects. In (Li et al., 2003; Megerian et al., 2005), the coverage problem is described as a quality of service problem, where the objective is to find how well, in terms of the quality of monitoring data, the field is monitored by the sensors. In (Berman et al., 2004; Cardei & Du, 2005; Cardei, Thai, Li & Wu, 2005; Slijepcevic & Potkonjak, 2001; Zhang & Hou, 2005; Zorbas et al., 2007), the problem is formulated as the maximisation of the network lifetime under the *area* or *target* coverage constraint. In the former formulation (see Figure 1left), the whole area (e.g. a big square region) must be monitored by the sensors, while in the latter the sensors must cover a set of points (targets) lying in the field (see Figure 1right). (Berman et al., 2004; Slijepcevic & Potkonjak, 2001; Wang & Kulkarni, 2008; Zhang & Hou, 2005; Zhong et al., 2002) deal with the area coverage problem. This chapter focuses on the target coverage problem, but it often refers to important works about other types of coverage that can help in the solution of the target coverage problem.
The most important challenge in a WSN is to efficiently manage the battery consumption of the sensors, since WSNs are characterized by limited energy resources and low computational capabilities. Managing the energy consumption in an efficient way can lead to an extension of the total network lifetime. In the case of the deterministic node placement this is translated as an optimal deployment of a set of sensors, where all the targets are covered. When the sensors

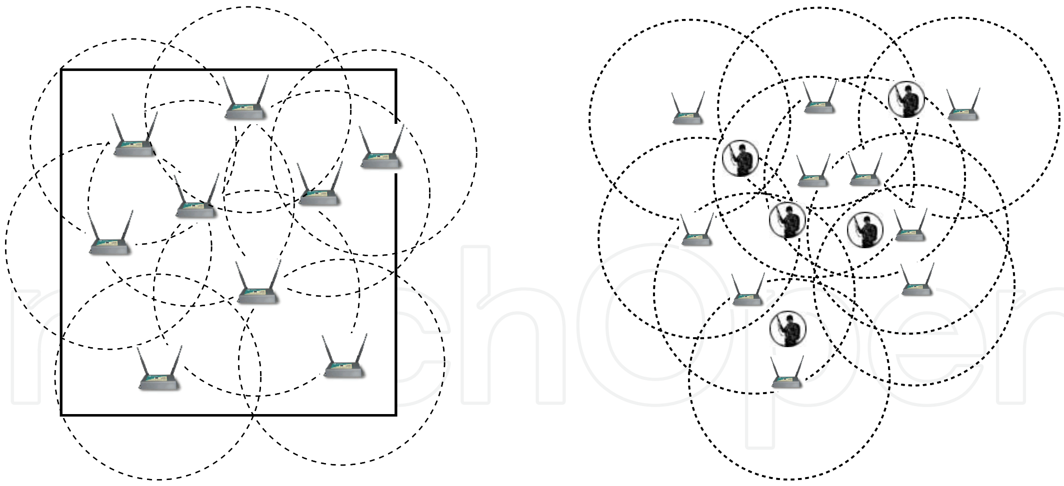

Fig. 1. Two major types of coverage: area and target coverage (The big square on the left denotes the covered area, the soldiers on the right denote the covered targets)

are randomly deployed, the energy management takes advantage of the ability of a sensor to put certain parts of the device into "sleep mode" and, thus, to consume less energy whenever it is not needed to perform monitoring or, more often, to participate in relaying tasks. This is achieved by dividing the sensors into sets, called *cover sets* or *sensor covers*, whereas each cover set can monitor all the available targets. Thus, only one set must be active at any time, while the rest of the sensors can be in sleep mode. Figure 2 illustrates two cover sets that provide full coverage.

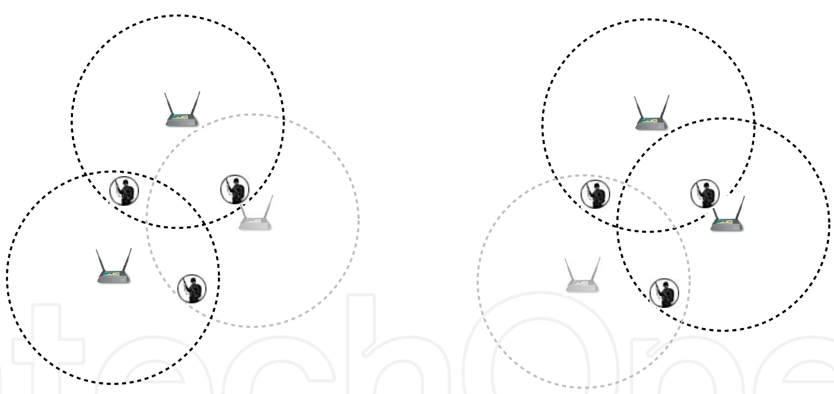

Fig. 2. Two generated cover sets (light grey colour denotes a node in sleep mode)

Next, we present the main works and solutions presented in the literature the past years, paying more attention to the random target coverage problem where a solid piece of work has been done. Furthermore, we classify the proposed solutions according to their objectives and present several variations of the target coverage problem.

2. Random target coverage

Most of the works in target coverage deal with the problem of dividing the sensors into cover sets and scheduling these sets consecutively such as only sensors belonging in one set are active at any time, while the rest are inactive. Assuming a random sensor deployment and the fact that each sensor consumes the same amount of energy in each cover set the coverage

problem is transformed to a problem of finding the optimal number of cover sets. Finding this optimal number is proven to be an NP-Complete problem (Cardei & Du, 2005), hence suboptimal solutions have been proposed in the literature such as algorithms based on linear programming, integer programming, greedy heuristics and branch and bound algorithms.
The proposed solutions can be separated into *centralised* and *distributed*. In a centralised coverage algorithm the monitoring schedule is first calculated on the base station and it is then sent to the sensor nodes for execution. The advantage of this scheduling approach is that it requires very low processing power from the sensor nodes, that usually have limited processing capabilities. A major disadvantage is the fact that the location of the sensors must be known in advance, which means that the sensors must me equipped with a global positioning system. Moreover centralised algorithms are not tolerant to the existence of corrupted nodes that can lead to a loss of data. In distributed algorithms the nodes usually use broadcasting in order to ensure connectivity with their neighbours and to detect failures.

2.1 Centralised algorithms

Below we analyse the basic characteristics of the existing centralised coverage scheduling algorithms that can be used in random sensor deployment scenarios with homogeneous device characteristics in terms of communication and sensing ranges. Many of the existing algorithms that deal with the maximisation of the number of cover sets incorporate a special strategy about the sensors that cover the most poorly covered targets. These targets are called *critical* and set an upper bound on the number of cover sets and, thus, on the achievable network lifetime. As described in (Zorbas et al., 2010) the number of cover sets is reduced as there are double-covered critical targets in a cover set. Moreover, regardless of the algorithmic approach (centralised or distributed) the cover sets can be assumed disjoint or non-disjoint. In disjoint cover sets a sensor can participate in only one cover set, while the opposite holds true in the non-disjoint case. In some cases the non-disjoint approach increases the overall network lifetime, but it incurs a higher complexity.

2.1.1 Disjoint approaches

Slijepcevic and Potkonjak (Slijepcevic & Potkonjak, 2001) propose a centralised algorithm for the area coverage problem. They introduce the idea of the *field* as a set of targets. Two targets belong to the same field if and only if they are covered by the same set of sensors. In particular, the fields are small areas which are produced by the intersection of the coverage limits of sensors and/or the physical limits of the monitoring terrain. As it shown in Figure 3, replacing each field (number) by a unique point (target), the area coverage problem is equivalent to the target coverage problem and, thus, the area coverage algorithms can be used to solve the target coverage problem as well.
Every sensor may cover one or more fields and one field is covered by at least one sensor. Their algorithm initially covers the *critical* fields (targets) and then it excludes all the other nodes that cover the same field. Thus, it is assured (during the construction of a cover set) that only one node covering a particular critical field shall be selected. This is a deterministic strategy in order to avoid the double-covering of the critical targets. The complexity of the algorithm is $O(n^2)$, where n is the total number of sensors.
Cardei *et al.* (Cardei et al., 2002) propose an algorithm to solve the same problem using graphs. They construct an undirected graph $G = (V, E)$, where V is the set of sensors and E the set of edges, such that the edge $(u, v) \in E$ if and only if u and v are within each other's sensing range. The goal is to find the maximum number of *dominating sets*. To achieve this a graph

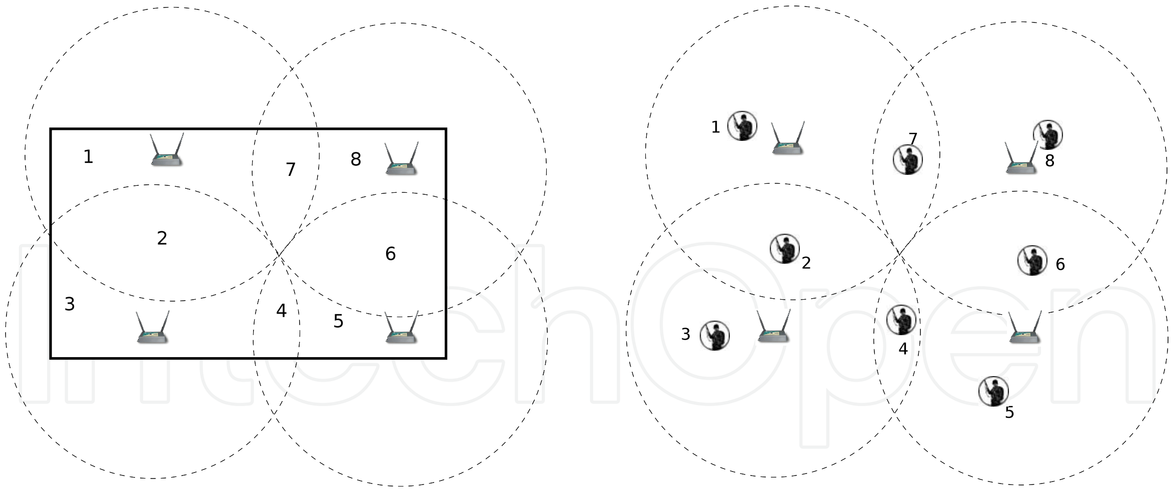

Fig. 3. Relation between area and target coverage

colouring technique is used. As depicted in (Thai et al., 2008), despite the production of more sets than the ones achieved in the proposal of (Slijepcevic & Potkonjak, 2001), the dominating sets do not guarantee the coverage of the whole area. The complexity of the heuristic which computes the disjoint sets from the coloured graph is $O(n^3)$.

Cardei and Du (Cardei & Du, 2005) propose a heuristic algorithm in order to solve the random target coverage problem. This problem is successively formulated as an area coverage problem, which is proved to be an NP-Complete problem. Cardei and Du define the disjoint-set coverage problem, that was first introduced by Slijepcevic and Potkonjak (Slijepcevic & Potkonjak, 2001), as a generalisation of the 3-SAT problem (Garey & Johnson, 1979). They propose a heuristic to compute the disjoint sets. In order to compute the maximum number of covers, they transform the problem into a maximum-flow problem. Then, the result of the maximum-flow problem is solved using *Mixed Integer Programming*, which heuristically produces the final number of cover sets. The results in (Cardei & Du, 2005) show a slight improvement in the number of produced sets in comparison to (Slijepcevic & Potkonjak, 2001) but there is a substantial increase of the execution time. The complexity of this algorithm depends on the complexity of the mixed integer programming technique used.

Finally, the work of (Liu et al., 2005) addresses the problem where given a set of sensors and targets, a sensor can watch only one target at a time. The objective is to schedule sensors to monitor targets, such that the lifetime of the surveillance system is maximized, where lifetime is defined as the duration of time when all targets are covered. This problem does not belong to the NP class, as it can be solved in polynomial time.

2.1.2 Non-disjoint approaches

Cardei *et al.* (Cardei, Thai, Li & Wu, 2005) propose a *Linear Programming* (LP) solution to the target coverage problem for non-disjoint cover sets as well. Although the LP algorithm presents a high complexity $O(m^3n^3)$, where m is the number of cover sets and n the number of sensors, the authors also propose a greedy algorithm with a lower complexity $O(dk^2n)$, where d is the number of sensors that cover the most poorly covered targets and k is the number of targets. The greedy algorithm is called Greedy-MSC and it uses a similar strategy to (Slijepcevic & Potkonjak, 2001) in order to avoid double-covering the critical targets.

In (Kim et al., 2009) the authors solve the same problem using a branch and bound algorithm. Their algorithm incorporates rules that decrease the probability of selecting two sensors that cover one or more similar targets. However, the authors do not give the complexity of their approach. The simulation results show a slight improvement of the network lifetime over the Greedy-MSC algorithm.

An LP technique is proposed by Berman *et al.* (Berman et al., 2004). In this approach first a series of cover sets is computed and then the optimal lifetime for each cover set is deduced. This approach is based on the $(1+\epsilon)$-approximation of the Garg and Könemann algorithm (Garg & Könemann, 1998), with an approximation factor of $(1+\epsilon)(1+2\ln n)$ for any $\epsilon > 0$.

In (Zorbas et al., 2010), the authors present a detailed methodology of how a greedy target coverage algorithm works and how it is possible to maximize the number of cover sets by efficiently managing the coverage status of the sensors and their association with the poorly covered targets. During the construction of a cover set, the sensor nodes are evaluated mainly based on their coverage status. Depending on the number of sensors that have been already covered in the examined cover set, the authors distinguish four kinds of sensor candidates, as shown in Figure 4. Candidates of the top two classes are more preferable as their selection is trouble free concerning the double-coverings, but they are fewer in number during the generation process.

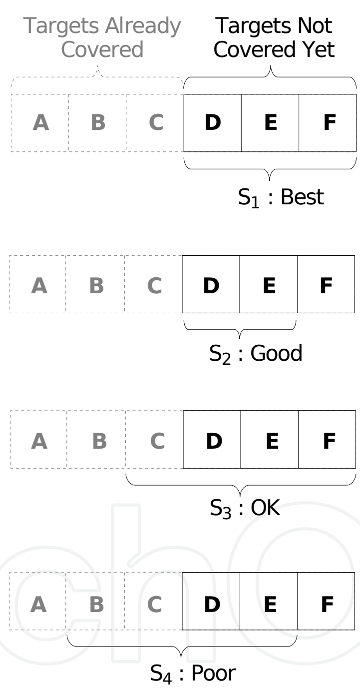

Fig. 4. The four classes of sensor candidates

Moreover, it is considered that all the available targets (i.e T_0) incorporate a degree of criticality based on the number of the sensors that they are covered by. The degree of criticality is formulated using the *badness* attribute. The badness, given by Formula (1), is calculated once for every sensor s_j at the beginning of the algorithm. N_i contains the sensors that cover the target t_i, P_j contains the targets that the sensor s_j covers, while μ is equal to $\max(|N_1|, \ldots, |N_k|), k = |T_0|$.

$$B_j = \sum_{i=1}^{|P_j|} (\mu - |N_i| + 1)^3 . \quad (1)$$

The badness attribute of a sensor describes the accumulative criticality level of all the targets covered by this sensor. This attribute can be used to prioritise the selection of sensor nodes that exhibit a low badness value (i.e., they are not as heavily associated with the targets of high degree of criticality). The advantage of the badness attribute compared to the deterministic strategy used in (Slijepcevic & Potkonjak, 2001) and (Cardei, Thai, Li & Wu, 2005) is that it is computed only once, thus achieving lower execution times.
The sensor candidates are evaluated using a complex cost function that takes into account three different characteristics: (a) the coverage status of the nodes, (b) their association to the poorly covered targets (badness) and (c) their remaining energy. Two heuristics are proposed, one based on the badness attribute and one based on the deterministic approach. The complexity of the approaches is $O(wn^2k)$, where w is a value that represents how many times a node can participate in the produced cover sets. The proposed algorithms are evaluated using 2-dimensional and 3-dimensional sensor and target deployments. The results show that the two heuristics present almost the same performance, which is very close or equal to the optimum, thus achieving constant execution times per generated cover set. The algorithm of (Slijepcevic & Potkonjak, 2001) exhibits an exponential increase in execution time, while the greedy heuristic of (Cardei, Thai, Li & Wu, 2005) requires the participation of a node in many cover sets in order to reach a satisfactory result, which comes at a cost in total execution time.
The following table presents a comparison between the algorithm that incorporates the badness attribute and the greedy heuristics of (Cardei, Thai, Li & Wu, 2005; Slijepcevic & Potkonjak, 2001).

	(Zorbas et al., 2010)	(Slijepcevic & Potkonjak, 2001)	(Cardei, Thai, Li & Wu, 2005)
Type of sets produced	Disjoint and non-disjoint	Disjoint	Disjoint and non-disjoint
Critical node handling	Prioritise nodes that cover targets with low criticality	Starts cover set with a critical node. Other nodes covering the same critical targets are ignored.	Starts cover set with a critical node. It does not implement any critical node avoidance strategy.
Candidate node selection criteria	a) # of uncovered targets vs. # of already covered b) # of available targets c) association with poorly monitoring targets d) remaining battery life	# of already covered targets the candidate covers	a) # of uncovered targets the candidate covers b) remaining battery life
Complexity	$O(wn^2k)$	$O(n^2)$	$O(dk^2n)$
Dense node deployment incurs significant penalty in execution time	No	Yes	Yes, due to increased number of participations required for optimal solution

Table 1. A comparison between centralised greedy algorithms of (Cardei, Thai, Li & Wu, 2005; Slijepcevic & Potkonjak, 2001; Zorbas et al., 2010)

2.2 Distributed and localised algorithms

In distributed and localised algorithms the decision whether a node will be in sleep mode or not is taken by the sensors. The nodes perform the required calculations cooperatively by communicating with their neighbours. These schemes may require some processing and a certain communication cost by the sensors involved, but they scale better to accommodate larger networks as well as networks with many sensor failures.
An important issue of the distributed and localised algorithms is the coverage synchronisation. In most cases the process is divided in rounds. During the synchronisation phase that

takes part before each round, the sensors decide whether they will be active or in sleep mode during the next coverage round. In target coverage the sensors exchange messages with their neighbours informing them about their coverage status and their *id*. Usually, the sensors that receive these messages evaluate them according to a cost function and the top scored node of the neighbourhood remains active during the next round. The problem rises when two or more nodes have a similar coverage status or cost function result. The nodes consider their selves as active (or sleep) in the same neighbourhood, leading to double covered targets (or uncovered targets). This issue is addressed in (Cardei & Cardei, 2008) by assigning back-off times to the sensors. The rationale behind this assignment is to give higher priority to sensors that have higher residual energy and cover a larger number of uncovered targets. When this time expires, a node declares itself as a sensing node during the next round. Additionally, it broadcasts this decision to all its 2-hop neighbours.

In (Tian & Georganas, 2002), the authors present a distributed and localised algorithm to solve the area coverage problem. They provide their solution as an extension to the well-known *LEACH* clustering protocol (Heinzelman et al., 2000). The process is divided into rounds and in every round two phases are distinguished: the self-scheduling and the sensing phase. During the self-scheduling phase the nodes investigate the off-duty eligibility rule. The eligibility rule determines whether a node's sensing area is included in its neighbours' sensing areas. Eligible nodes turn off their communication and sensing units to save energy. Non-eligible nodes perform sensing tasks during the sensing phase. The sensing phase is much longer than the self-scheduling phase. The authors incorporate a scheme in order to avoid the appearance of blind points (uncovered areas). They do not deal with the connectivity requirement, leaving this task to the data gathering protocol. Making this assumption this algorithm can be used to solve the target coverage problem as well.

In (Ye et al., 2002), the authors use a probing based scheme in order to determine which sensor will be active. In this scheme a sleeping node wakes up after sleeping for an exponentially distributed period of time specified by a wakeup rate. After a sleeping node wakes up, it broadcasts a probing message within a range r. When hearing a probing message, any working node within this range will locally broadcast a reply message. If the wakeup node hears a reply message, it knows that there is a working node within distance r and the node goes back to the sleeping mode. If the wakeup node does not hear a reply message within a prespecified time interval, it assumes that no working node is within its probing range and it starts working continually. It must be noted that this algorithm controls the active node density and may not provide full coverage. Moreover, since this algorithm is developed for the area coverage problem, a scheme using relay nodes that ensures connectivity must be provided in order to be able to use this algorithm in the target coverage problem.

2.3 Incorporating connectivity

More recent works in the literature take into account the connectivity requirement that appears in multi-hop networks. Considering this requirement it is not possible to use the area coverage algorithms to solve the target coverage problem as well. The problem derives from the fact that in area coverage if the communication range is at least twice the length of the sensing range coverage implies connectivity (Zhang & Hou, 2005). In target coverage the issue that must be addressed concerns the finding of the maximum number of cover sets, while every node in each cover set in multi-hop networks remains connected with the BS using relay nodes (see Figure 5. This problem often translates to the computation of paths with the minimum possible cost since the consumed energy rises with the distance between two nodes.

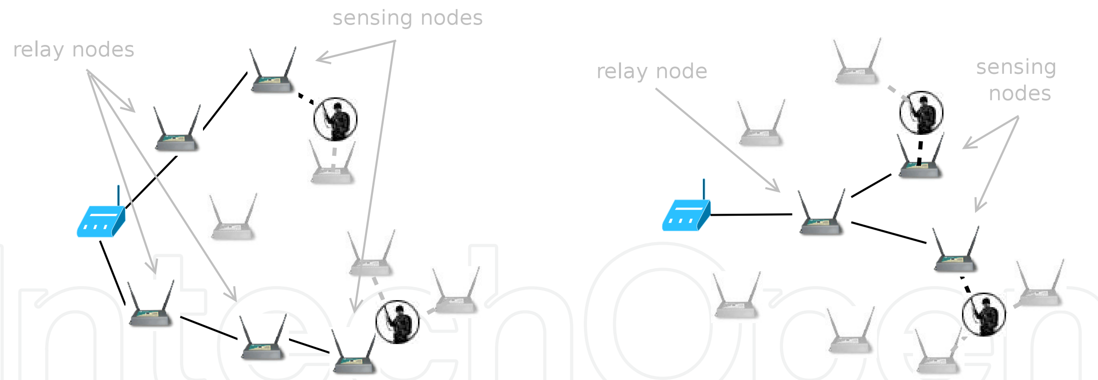

Fig. 5. Two cover sets that are connected with a base station

In (Cardei & Cardei, 2008), centralised and distributed algorithms are proposed for the computation of the connected cover sets. A breadth first search algorithm is used to discover the node-path to the BS through a centralized algorithm, while a minimum spanning tree algorithm is used in the distributed version of the algorithm.
In (Jaggi & Abouzeid, 2006), it is proposed another connected cover set generation algorithm in order to extend the lifetime of the network. They consider that all the cover sets are disjoint and they try to maximize their number, while they compute a shortest path tree to select the relay nodes that manage to retain connectivity in the network.
These two works use a simplified energy consumption model. The energy consumed for communication is predefined for all sensors and it does not depend on the distance between the nodes, which is far from true in a real network environment. It is, also, assumed that each sensor consumes the same amount of energy, regardless of the number of targets it covers. In real-time WSNs the consumed energy increases with the distance between the nodes, while the amount of the transmitted data depends on the size of the packets and the degree of the data aggregation that may used.
In (Zhao & Gurusamy, 2008b), the authors model the connected target coverage problem as a maximum cover tree problem. A theoretical analysis of the problem shows that it is also NP-Complete. An approximation algorithm as well as a greedy one with a lower computation cost are proposed. Connectivity, coverage and a practical energy consumption model that is based on distance are taken into account. The network is modelled as a graph, where the vertices correspond to the nodes and the edges to the links between two sensors. The greedy algorithm applies weights on the edges of the graph of nodes in order to select nodes with high remaining energy and low communication cost. However, it requires a re-computation of all the weights of the graph, each time a new cover set is generated and no policy is applied about the critical targets.

3. Other types of target coverage

3.1 Deterministic target coverage

The objective in deterministic target coverage is to deploy a minimum number of sensors in order to cover a set of targets and apply connectivity to the network. This problem is addressed by (Kar & Banerjee, 2003), where the authors consider a 2-dimensional region with randomly deployed targets. They propose a polynomial time algorithm with a performance ratio of 7.256 when the communication range is equal to the sensing range.

In (Dasgupta et al., 2003), the authors address the problem of placing a given number of sensors in order to cover a set of targets and at the same time to maximise the lifetime of the network. They consider a realistic energy consumption model where the consumed energy increases with the distance. The process is divided in rounds and in every round they try to minimise the energy consumption per node by balancing the traffic among the appropriate relay nodes. The simulation results show an over 40% improvement over the random node deployment case.
Finally, authors in (Wang et al., 2006) formulate the problem considering a sensing model where the sensing signal weakens when the target is in a long distance away from the sensor. Moreover, each target has a degree of importance called the *utility*. Based on these parameters the authors develop a greedy heuristic algorithm to find the optimal positions of the sensors.

3.2 Adjustable sensing ranges

The works of (Cardei, Wu, Lu & Pervaiz, 2005; Dhawan et al., 2006; Lu et al., 2009) deal with the target coverage problem where the sensors can adjust their sensing range in order to conserve energy. The sensor of (Migatron, n.d.) has an adjustable two to six inch sensing range with background suppression, that means that any object within the desired range is detected, while objects out of the desired range are ignored. A network with three sensors with adjustable sensing ranges and four targets is illustrated in Figure 6.

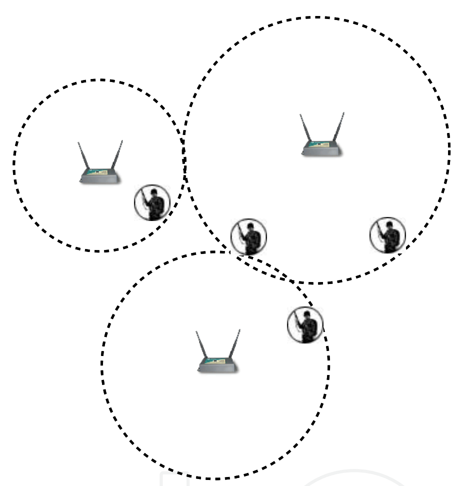

Fig. 6. Three sensors with adjustable sensing ranges cover four targets

In (Cardei, Wu, Lu & Pervaiz, 2005), the authors divide the sensors in cover sets, where the sensors of each cover set adjust their sensing range in order to avoid covering the same targets two or more times. The authors examine the case where the nodes' sensing range has p steps, while they target to maximise the number of cover sets. They present an LP-based solution, a centralised greedy one and a distributed and localised algorithm. They assume a linear and an exponential energy consumption model for the sensing operation. The simulation results show that the consumed energy can be reduced in half compared to the approach where the sensors have the longest possible sensing range.
Unlike (Cardei, Wu, Lu & Pervaiz, 2005), in (Dhawan et al., 2006), it is assumed that each sensor has an infinite number of options concerning its sensing range. The authors propose an approximate algorithm to solve this problem based on Garg and Könemann algorithm (Garg & Könemann, 1998). Their simulation results show an significant improvement over the distributed algorithm of (Cardei, Wu, Lu & Pervaiz, 2005).

The previous two works do not take into account the connectivity requirement. The work of (Lu et al., 2009) presents an extension of the work of (Cardei, Wu, Lu & Pervaiz, 2005), where target coverage and connectivity are maintained. The authors present a distributed algorithm that builds a virtual backbone first to satisfy network connectivity, and they ensure coverage based on that backbone. In providing such a virtual backbone, the authors first construct a connected dominating set and prune redundant sensors by applying the Rule-k algorithm (Dai & Wu, 2003).

3.3 Partial target coverage

In applications where the full coverage is not a critical requirement, algorithms that provide partial coverage can be used. Such applications are those where the data provided by a subset of the available targets are satisfactory for the required measurements. Partial coverage has been first studied for the area coverage problem. Partial area coverage deals with the maximization of the α-lifetime with a minimum amount of energy, where α denotes the coverage percentage of the total monitoring area (i.e. $0 < \alpha \leq 1$). In target coverage this means the percentage of the total number of covered targets.

Abrams et al (Abrams et al., 2004) propose centralised and distributed algorithms to solve the coverage problem, as well as a randomised algorithm with performance guarantee. Each generated cover set does not provide complete coverage and the cover sets must be scheduled successively in order to achieve at least the 72% of the monitored areas.

In (Wang & Kulkarni, 2008), the authors describe a localized protocol for the area coverage problem, called *pCover*. The protocol tries to maintain a high degree of coverage (over 90%), but it also produces an increased surveillance time compared to the full coverage approach. The simulation results provided show an improvement of 2 to 7 times compared to the total coverage duration. However, the connectivity of the network is not guaranteed in this solution.

In (Yan et al., 2003) an adaptive algorithm that adjusts the degree of coverage depending on the problem requirements is proposed. The degree of coverage can be either lower or higher than one, depending on the node deployment density. This approach can be used in applications where the coverage requirements are changing during the monitoring process. The connectivity is still an open problem whenever the degree of coverage is below one.

In (Liu & Liang, 2005), the objective is to not only to find a subset of sensors for partial coverage with a given coverage guarantee, but also to ensure that the communication graph induced by the chosen sensors is connected. To achieve this the authors propose the use of a shortest path tree and a cost function based on the total area that a sensor candidate covers. According to the simulation results the network lifetime can be prolonged over three times compared to the full coverage approach.

Even though the previous works have been developed for the area coverage problem, they can be also used for the target coverage problem without ensuring connectivity. The work of (Zorbas et al., 2009) introduces the partial target coverage problem, where two neighbouring targets may not be covered in the same cover set, as it is considered that they may provide similar data. However, this decision is taken by a parameter that uses the Euclidean distance between two or more targets and not by a scheme that is based on geographical or statistical information from the past data collections. The overall number of covered targets per cover set is controlled by a user-given value. The proposed centralised solution incorporates the connectivity constraint and compared to the full coverage approach of (Zhao & Gurusamy, 2008b) can double the overall network lifetime covering the 90% of the targets.

3.4 Target coverage under QoS constraint

In applications where the quality of the monitoring data is critical in terms of robustness and accuracy, all or some of the targets may be covered by more than one sensor per time. This problem is defined in the literature as the k-coverage problem or the QoS-aware coverage problem. This technique is, also, useful in environments with many node failures as it provides a shield against possible loss of data.

In (Zhou et al., 2004), the connected k-coverage problem is addressed. The authors propose centralised and distributed algorithms that select a minimum number of sensors that provide connectivity and cover each point in a given query region with at least k distinct sensors. The idea is to keep only those sets of sensors active to provide the necessary coverage and connectivity, resulting in a fault-tolerant energy conservation technique.

The works of (Hefeeda & Bagheri, 2006; Simon et al., 2007) and (Vu et al., 2006) deal with the k-coverage problem where the connectivity is ensured if the communication range is at least twice the sensing range. The authors propose efficient centralised and distributed algorithms, but a connectivity scheme is required to use them in the target coverage problem.

In (Zhao & Gurusamy, 2008a), the authors deal with the k-target coverage problem, while they take into account the network connectivity. They develop an optimal solution based on an LP formulation and an efficient approximation algorithm to solve it. They, also, present a low cost greedy heuristic algorithm that is useful for practical implementations. The connectivity in the greedy algorithm is achieved using a shortest path tree. The simulation results of the greedy algorithm are very close to the optimum (LP algorithm).

The problem of coverage where each sensor has different coverage requirements (Q-coverage problem) is examined in (Gu et al., 2009). The authors design a general optimization architecture using linear programming techniques that contains a lifetime upper bound and a column generation based approach. However, the network connectivity is not included in their method.

In addition, the k-coverage problem has been described from many other different aspects. In (Shen & Wu, 2010) a Minimum Movement-assisted k-Coverage deployment problem is formulated, where a minimum set of sensors are selected and relocated to appropriate positions such that each point in the entire region is covered by at least k sensors. In (Liu et al., 2008) the problem of Directional k-Coverage (DKC) in camera-equipped sensor networks is addressed. The DKC problem is different from the one addressed in conventional sensor networks due to the directionality of the sensing model and the effective sensing. In (Kim et al., 2007), a distributed k-coverage algorithm is presented that leaves a small number of areas uncovered. The paper of (Ammari & Giudici, 2009) focuses on the problem of connected k-coverage in heterogeneous wireless sensor networks, while in (Ammari & Giudici, 2009) the k-coverage problem is examined in the presence of sensor mobility. Finally, in (Ammari & Das, 2010), the problem of connectivity and k-coverage in 3D WSNs is addressed.

3.5 Target coverage under bandwidth constraint

In applications where a large amount of data (e.g. video data) is required to be delivered and the time division protocol of the sink has a limited number of available time slots, the sensors of each cover set can transmit a limited amount of bytes. If this number of nodes is large and the interval between consecutive reports of the same target is critical for the applications, a *coverage breach* may occur (Cheng et al., 2007). In a case of a breach several targets may remain uncovered for a period of time.

In (Cheng et al., 2005), the target coverage problem under a bandwidth constraint is formulated as the minimum breach problem where the objective is to divide the sensors in disjoint cover sets while in each cover set the maximum possible number of targets is covered. Each cover set contains a maximum number of sensors equal to the available time slots (i.e. W). The authors prove that it is an NP-Complete problem and they transform it to an integer programming problem.
The work of (Cheng et al., 2007) is an extension to the previous work. The authors analyse three instances of the problem; the minimum breach, the minimum individual breach time and the minimum maximal breach. The objective of the first instance is to find a user given number of cover sets when the cardinality of each cover set must be smaller than $W + 1$ and the total breach is minimised. The other two instances consider a maximum allowed breach time and a maximum number of cover sets that must be computed. Two algorithms are proposed to solve the above problems; a greedy one and an LP-based.
In (Wang et al., 2007) two equivalent instances of the coverage breach problem with those of (Cheng et al., 2007) are presented. The objective in the first instance is to achieve a maximum amount of network lifetime by minimizing the total breach time, while in the second one a maximum value of the breach rate is allowed, while the lifetime must be maximised. The authors allow a sensor node to be a member of multiple cover sets. In order to solve the above instances of the problem they propose an LP-based algorithm and a greedy heuristic.
While in the previous approaches the network connectivity is not taken into account, the work of (Zorbas & Douligeris, 2009) presents a greedy heuristic that produces connected cover sets under the bandwidth constraint. The authors compare their solution to the previous approaches in 1-hop environments. The results show that their approach present a slightly lower number of cover sets, but each cover set is capable of monitoring more targets than the other approaches. Concerning the multi-hop networks, the simulation results show that the connectivity constraint and the increased needs of data limit the lifetime of the network due to the energy exhaustion of the nodes that must transmit the data to the sink.

4. Conclusions

This chapter analysed the target coverage problem in wireless sensor networks under the constraint of the power efficiency. Recent works found in the literature have been described and organised according to the objectives of the coverage approach. Depending on the requirements of the particular application many different design approaches have been presented. The classic target coverage problem can be used for military purposes and the sensor deployment may be random or deterministic.
Since the most likely way to achieve energy efficiency is to divide sensors in groups (cover sets), where only one group is active at any time instant, this chapter focused on the works that address the problem of finding the maximum number of disjoint or non-disjoint cover sets. WSNs usually operate in a multi-hop manner, hence the network connectivity is always a critical requirement for the target coverage surveillance.
Moreover, the power efficient target coverage problem can be observed under further practical constraints. These constraints can either reduce the energy consumption, (adjustable sensing ranges and partial coverage), or increase the availability and the reliability of the monitoring data (QoS constraint). Finally, in applications with a high flow of data, as the camera-equipped sensor networks, efficient algorithms that minimise the number of uncovered targets have also been presented in this chapter. Table 2 summarises the works described in this chapter. Since

Reference	Objectives & characteristics	Algorithmic approach	Network connectivity
Slijepcevic & Potkonjak (2001)	Maximise the number of cover sets (1)	Centralised	no
Cardei et al. (2002)	(1)	Centralised	no
Berman et al. (2004)	(1)	Centralised & distributed	no
Cardei & Du (2005)	(1)	Centralised	no
Cardei, Thai, Li & Wu (2005)	(1)	Centralised	no
Zorbas et al. (2007)	(1)	Centralised	no
Kim et al. (2009)	(1)	Centralised	no
Zorbas et al. (2010)	(1)	Centralised	yes, but only between sensing nodes
Liu et al. (2005)	(1), a sensor covers only one target	Centralised	no
Tian & Georganas (2002)	Minimise the number of active nodes (2)	Distributed	no for target coverage
Ye et al. (2002)	(2)	Distributed	no for target coverage
Cardei & Cardei (2008)	(1)	Centralised & distributed	yes
Jaggi & Abouzeid (2006)	(1)	Centralised	yes
Zhao & Gurusamy (2008b)	Maximise the lifetime of each cover set & the network lifetime (3)	Centralised	yes
Kar & Banerjee (2003)	Minimise the number of deployed nodes (4)	–	yes
Dasgupta et al. (2003)	Deploy a number of sensors & maximise the netw. lifetime	Distributed	yes
Wang et al. (2006)	(4)	–	no for target coverage
Cardei, Wu, Lu & Pervaiz (2005)	(1), adjustable sensing ranges	Centralised & distributed	no
Cardei, Wu, Lu & Pervaiz (2005)	(1), adjustable sensing ranges	Centralised	no
Lu et al. (2009)	(1), adjustable sensing ranges	Centralised & distributed	yes
Abrams et al. (2004)	(1), partial coverage	Centralised & distributed	no for target coverage
Wang & Kulkarni (2008)	(2), partial coverage	Distributed	no
Yan et al. (2003)	(2), partial or over-coverage	Distributed	no
Liu & Liang (2005)	(1), partial coverage	Centralised	yes
Zorbas et al. (2009)	(3), Partial coverage	Centralised	yes
Zhou et al. (2004)	(2), *k*-coverage	Centralised & distributed	yes
Simon et al. (2007)	(2), *k*-coverage	Centralised & distributed	no for target coverage
Hefeeda & Bagheri (2006)	(1), *k*-coverage	Centralised & distributed	no for target coverage
Vu et al. (2006)	(1), *k*-coverage	Distributed	no for target coverage
Zhao & Gurusamy (2008a)	(2), *k*-coverage	Centralised	yes
Gu et al. (2009)	(1), *Q*-coverage	Centralised	no
Cheng et al. (2005)	(1) under bandwidth constraint (5)	Centralised	no
Cheng et al. (2007)	(5)	Centralised	no
Wang & Kulkarni (2008)	(5)	Centralised	no
Zorbas & Douligeris (2009)	(5)	Centralised	yes

Table 2. A summary of works related to the target coverage problem

the network lifetime is strongly connected with the coverage and connectivity, these works are considered as an important factor in designing energy efficient sensor networks.
The most recent efforts in the area of coverage involve the usage of mobile sensor nodes. With the growth of robotics the sensors will be able to move across the field and collect data from inaccessible places. This ability will make sensor networks more desirable in dynamic battlefields, where the targets are mobile and multiple unpredictable events occur. Undoubtlessly, the coverage and communication in these environments require the development of robust, reliable and long lived networks that operate in a distributed way. Moreover, the recent advances in microelectronics, chemistry and solar systems will lead to the development of self-powered small devices that will operate for almost infinite period of time increasing the availability of the networks, specially in the case of hostile environments.

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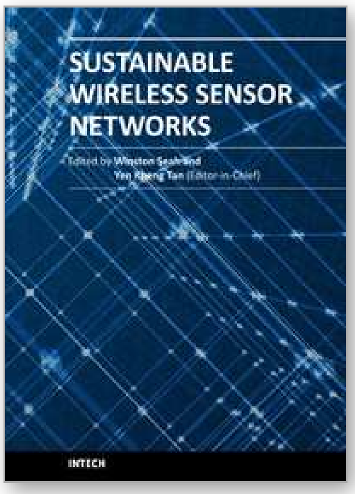

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Wireless Sensor Networks came into prominence around the start of this millennium motivated by the omnipresent scenario of small-sized sensors with limited power deployed in large numbers over an area to monitor different phenomenon. The sole motivation of a large portion of research efforts has been to maximize the lifetime of the network, where network lifetime is typically measured from the instant of deployment to the point when one of the nodes has expended its limited power source and becomes in-operational â€“ commonly referred as first node failure. Over the years, research has increasingly adopted ideas from wireless communications as well as embedded systems development in order to move this technology closer to realistic deployment scenarios. In such a rich research area as wireless sensor networks, it is difficult if not impossible to provide a comprehensive coverage of all relevant aspects. In this book, we hope to give the reader with a snapshot of some aspects of wireless sensor networks research that provides both a high level overview as well as detailed discussion on specific areas.