Energy-efficient coverage problems in wireless ad-hoc sensor networks

Mihaela Cardei*, Jie Wu

Department of Computer Science and Engineering, Florida Atlantic University, Boca Raton, FL 33431, USA

Available online 23 February 2005

Abstract

Wireless sensor networks constitute the platform of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring. The *sensor coverage problem* has received increased attention recently, being considerably driven by recent advances in affordable and efficient integrated electronic devices. This problem is centered around a fundamental question: *How well do the sensors observe the physical space?* The coverage concept is subject to a wide range of interpretations due to a variety of sensors and their applications. Different coverage formulations have been proposed, based on the subject to be covered (area versus discrete points) and sensor deployment mechanism (random versus deterministic) as well as on other wireless sensor network properties (e.g. network connectivity and minimum energy consumption). In this article, we survey recent contributions addressing energy-efficient coverage problems in the context of static wireless sensor networks. We present various coverage formulations, their assumptions, as well as an overview of the solutions proposed.

1. Introduction

Wireless sensor networks (WSNs) have attracted a great deal of research attention due to their wide-range of potential applications. WSNs provide a new class of computer systems and expand the ability of individuals to remotely interact with the physical world. In a broad sense, WSNs will transform the way we manage our homes, factories, and environment. Applications of WSNs [10] include battlefield surveillance, biological detection, home appliance, smart spaces, and inventory tracking.

The purpose of deploying a WSN is to collect relevant data for processing/reporting. There are two types of reporting [3]: *event-drive* and *on-demand*. Consider a WSN with a sink (also called monitoring station) and a set of sensor nodes. In the event-driven reporting, the reporting process is triggered by one or more sensor nodes in the vicinity which detect an event and report it to the monitoring station. In the on-demand report, the reporting process is initiated from the monitoring station, and sensor nodes send their data in response to an explicit request. A forest fire monitoring system is event-driven, whereas an inventory control system is on-demand. A more flexible system can be a hybrid of event-driven and on-demand.

Sensor nodes are tiny devices equipped with one or more sensors, one or more transceivers, processing and storage resources and, possibly, actuators. Sensor nodes organize into networks and collaborate to accomplish a larger sensing task. One important class of WSNs is wireless ad-hoc sensor networks (WASN), characterized by an 'ad-hoc' or *random* sensor deployment method [16], where the sensor location is not known a priori. This feature is required when individual sensor placement is infeasible, for example battlefield or disaster areas. The characteristics of a WASN include limited resources, large and dense networks, and dynamic topology. Generally, more sensors are deployed than required (compared with the optimal placement) to perform the proposed task; this compensates for the lack of exact positioning and improves the fault tolerance. The size of a WASN may reach hundreds or even thousands of sensor nodes. If the sensors can be placed exactly where they are needed (e.g. in friendly or accessible environments), the corresponding deployment method is *deterministic* [12].

An important problem addressed in literature is the *sensor coverage problem*. This problem is centered around

---

* Corresponding author. Tel.: +1 5612973459; fax: +1 5612972800.
E-mail address: mihaela@cse.fau.edu (M. Cardei).

a fundamental question: 'How well do the sensors observe the physical space?' As pointed out in [14], the coverage concept is a measure of the quality of service (QoS) of the sensing function and is subject to a wide range of interpretations due to a large variety of sensors and applications. The goal is to have each location in the physical space of interest within the sensing range of at least one sensor.

In this paper, we survey recent contributions addressing energy-efficient coverage problems in the context of static WASNs, networks in which sensor nodes do not move once they are deployed. Sensors have omnidirectional antennae and can monitor a disk centered at the sensor's location, whose radius equals the sensing range.

Energy-efficiency is an important issue in WASN, because battery resources are limited. Mechanisms that conserve energy resources are highly desirable, as they have a direct impact on network lifetime. Network lifetime is in general defined as the time interval the network is able to perform the sensing functions and to transmit data to the sink. During the network lifetime, some nodes may become unavailable (e.g. physical damage, lack of power resources) or additional nodes might be deployed. A frequently used mechanism is to schedule the sensor node activity such that to allow redundant nodes to enter the *sleep* mode as often and for as long as possible. To design such a mechanism, one must answer the following questions: (1) Which rule should each node follow to determine whether to enter sleep mode? (2) When should nodes make such a decision?, and (3) How long should a sensor remain in the sleep mode?

Another method to reduce power consumption is to minimize the sensing range, while the sensing coverage objective is met. If adapting the sensing range is allowable, the sensors in the active mode should dynamically adjust their sensing range to a minimum value such that the overall sensing objective is met. The same principle can also apply to the sensors' communication range. If a sensor has the option to adjust its communication range, power savings can be obtained when minimizing the communication range while maintaining the connectivity requirements.

In this paper we present various energy-efficient coverage formulations and their assumptions, as well as an overview of solutions proposed. In Section 2, we give a general overview of the various design choices and related work. In Sections 3 and 4, we discuss two types of coverage: area coverage and point coverage, with focus on energy-efficient designs. The paper concludes in Section 5 with discussions and future trends in this area.

2. Sensor coverage problems and design choices

We first give an overview of design choices for sensor coverage problems and then discuss related work in other fields.

2.1. Design choices

Sensors have size, weight, and cost restrictions, which impact resource availability. They have limited battery resources and limited processing and communication capabilities. As replacing the battery is not feasible in many applications, low power consumption is a critical factor to be considered, not only in the hardware and architectural design, but also in the design of algorithms and network protocols at all layers of the network architecture. Therefore maximizing the network lifetime is an important network design objective. Using a minimum number of sensors is another clear objective, especially in a deterministic node deployment approach.

A sensor node's radio can be in one of the following four states: transmit, receive, idle, or sleep. The idle state is when the transceiver is neither transmitting nor receiving, and the sleep mode is when the radio is turned off. As presented in [17], an analysis of the power usage for WINS Rockwell seismic sensor indicates power consumption for the transmit state between 0.38 and 0.7 W, for the receive state 0.36, for the idle state 0.34 W and for the sleep state 0.03 W. The power consumed for the sensing task is 0.02 W. An interesting observation is that the receive and idle modes may require as much energy as transmitting, whereas in the traditional ad-hoc wireless networks, transmitting may use as high as twice the power of receiving. Another observation is the communication/computation power usage ratio, which can be higher than 1000 (e.g. for Rockwell WINS [17] is from 1500 to 2700), therefore local data processing, data fusion and data compression are highly desirable. Judiciously selecting the state of each sensor node's radio is accomplished through a *scheduling* mechanism. This constitutes an important method for decreasing the network energy consumption when the goal is to reduce the number of active sensors performing the coverage task. Sometimes, the scheduling mechanism also has the objective of maintaining connectivity among active sensors.

The coverage algorithms proposed are either *centralized* or *distributed*. In distributed algorithms, the decision process is decentralized. By distributed and localized algorithms, we refer to a distributed decision process at each node that makes use of only neighborhood information, within a constant number of hops. Because the WASN has a dynamic topology and needs to accommodate a large number of sensors, the algorithms and protocols designed should be distributed and localized, in order to better accommodate a scalable architecture.

The most discussed coverage problems in literature can be classified in the following types: area coverage, point coverage and barrier coverage. Based on the subject to be covered (*area* versus *discrete points*), different problems can be formulated considering the following design choices:

- *Sensor deployment method*: deterministic versus random. A deterministic sensor placement may be feasible in

Table 1
Coverage approaches with random sensor deployment

Coverage approach	Coverage type	Problem objectives
Most constrained-minimally constraining heuristic [19]	Area coverage	(1) energy-efficiency and (2) maximize network lifetime by reducing the number of working nodes
Disjoint dominating sets heuristic [1]	Area coverage	same objectives as above
Node self-scheduling algorithm [20]	Area coverage	same objectives as above
Probing-based density control algorithm [25]	Area coverage	(1) energy-efficiency and (2) maximize network lifetime by controlling working nodes density
Optimal geographical density control (OGDC) algorithm [26]	Area coverage	(1) energy-efficiency, (2) connectivity, and (3) maximize network lifetime by reducing the number of working nodes
Coverage con_guration protocol (CCP) [21]	Area coverage	same objectives as above
Connected dominating set based coverage [22]	Area coverage	same objectives as above
Connected area dominating sets [3]	Area coverage	same objectives as above
Disjoint set cover heuristic [2]	Point coverage	(1) energy-efficiency and (2) maximize network lifetime by reducing the number of working nodes

friendly and accessible environments. Random sensor distribution is generally considered in remote or inhospitable areas, or for military applications.

- *Sensing and communication ranges*: WASN scenarios consider sensor nodes with same or different sensing ranges. Another factor that relates to connectivity is communication range, that can be equal or not equal to the sensing range.
- *Additional critical requirements*: energy-efficiency and connectivity. We will refer to these as energy-efficient coverage and connected coverage.
- *Algorithm characteristics*: centralized versus distributed/localized.
- *Objective of the problem*: coverage, maximum network lifetime or minimum number of sensors.

Area coverage and point coverage problems are defined in Sections 3 and 4, respectively.

We consider the barrier coverage as being the coverage with the goal of minimizing the probability of undetected penetration through the barrier (sensor network). Such a coverage model is proposed by Meguerdichian et al. in [14], where the following problem is addressed: given a feld instrumented with sensors and the initial and final locations of an agent that needs to move through the field, determine a maximal breach path (MBP) and the maximal support path (MSP) of the agent. The MBP (MSP) corresponds to the worst (best) case coverage and has the property that for any point on the path, the distance to the closest sensor is maximized (minimized). The model assumes homogeneous sensor nodes, known sensor locations (e.g. through GPS), with sensing effectiveness decreasing as the distance increases. The authors proposed a centralized solution, based on the observation that MBP lies on the Voronoi diagram lines and MSP lies on Delaunay triangulation lines.

Another barrier coverage is the *exposure-based model*, introduced by Meguerdichian et al. in [15]. Here, the sensing abilities of the sensors diminish as the distance increases, and an important factor considered is the sensing time (exposure). The longer the exposure time, the greater the sensing ability. Given a field instrumented with *n* sensors and the initial and final points of the object, the authors propose a centralized solution to the problem of determining the minimal exposure path.

According to the design choices presented above, Tables 1 and 2 summarize the energy-efficient area and point coverage methods that will be described in Sections 3 and 4.

2.2. Coverage problem in other fields

Coverage problems have been formulated in other fields. These problems include the Art Gallery Problem, ocean coverage, and robotic systems coverage.

The art gallery problem [18] requires determining the number and placement of observers necessary to cover an art gallery room such that every point is seen by at least one observer. This problem has a linear time solution for the 2*D* case. The 3*D* version is NP-hard and an approximation

Table 2
Characteristics of approaches listed in Table 1

Coverage approach	Sensing range R_s, comm. range R_c		Algorithm characteristics
	Same R_s for all sensors?	Is $R_s = R_c$ for each sensor?	
[19]	Yes	NA	Centralized
[1]	Yes	NA	Centralized
[20]	Yes + no (both)	NA	Distributed, localized
[25]	Yes	NA	Distributed, localized
[26]	Yes	NO	Distributed, localized
[21]	Yes	NO	Distributed, localized
[22]	Yes	YES	Distributed, localized
[3]	Yes	YES	Distributed, localized
[2]	Yes	NA	Centralized

algorithm is presented in [13]. This visibility problem has many real world applications, such as placement of antennas for cellular telephone companies, and placement of cameras for security purposes in banks and supermarkets.

The work in [7] addresses the ocean area coverage problem. Here the authors are interested in satellite based monitoring of the ocean phytoplankton abundance. This paper assesses whether assembling and merging data from more satellites would improve the ocean coverage, since various impairments prevent any single satellite from observing more than 15% of the ocean surface in a single day. Given the orbit and sensor characteristics of each mission, numerical analysis results show that merging data from three satellites can increase ocean coverage by 58% for one day and 45% for four days. Still additional satellites produce diminishing returns.

The coverage concept with regard to the many-robot systems was introduced by Gage [6]. He defined three types of coverage: blanket coverage, barrier coverage, and sweep coverage. In blanket coverage, the goal is to achieve a static arrangement of sensors that maximizes the total detection area. In barrier coverage the goal is to achieve a static arrangement of nodes that minimizes the probability of undetected penetration through the barrier, whereas the sweep coverage is more or less equivalent to a moving barrier. New applications arise in the context of mobile WASNs, where sensors have locomotion capabilities. Thus, the nodes can spread out to maximize the area covered by the network (e.g. [9]) and can relocate to handle sensor failures.

3. Energy-efficient area coverage

The most studied coverage problem is the area coverage problem, where the main objective of the sensor network is to cover (monitor) an area (also referred sometimes as region). Fig. 1(a) shows an example of a random deployment of sensors to cover a given square-shaped area, where circles represent the sensing range. Each point of the area is monitored by at least one sensor. The connected black nodes
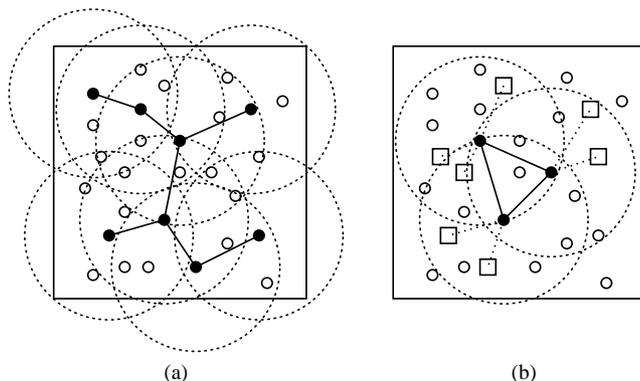
Fig. 1. (a) Area coverage and (b) Point coverage.

form the set of active sensors, the result of a scheduling mechanism. Next, we survey recent energy-efficient area coverage problem formulations, their models and assumptions, as well as solutions proposed.

3.1. Energy-efficient coverage

The works in [1] and [19] consider a large population of sensors, deployed randomly for area monitoring. The goal is to achieve an energy-efficient design that maintains area coverage. As the number of sensors deployed is greater than the optimum required to perform the monitoring task, the solution proposed is to divide the sensor nodes into disjoint sets, such that every set can individually perform the area monitoring tasks. These sets are then activated successively, and while the current sensor set is active, all other nodes are in a low-energy sleep mode. The goal of this approach is to determine a maximum number of disjoint sets, as this has a direct impact on conserving sensor energy resources as well as on prolonging the network lifetime. The solutions proposed are centralized.

Slijepcevic and Potkonjak [19] model the area as a collection of fields, where every field has the property that any enclosed point is covered by the same set of sensors. The most-constrained least-constraining algorithm [19] computes the disjoint covers successively, selecting sensors that cover the critical element (field covered by a minimal number of sensors), giving priority to sensors that: cover a high number of uncovered fields, cover sparsely covered fields and do not cover fields redundantly.

Cardei et al. [1] model the disjoint sets as disjoint dominating sets in an undirected graph, where sensors form the vertex set and an edge joins any two vertices that are within each other's sensing range. The maximum disjoint dominating sets computation is NP-complete, and any polynomial-time approximation algorithm has a lower bound of 1.5. A graph-coloring mechanism is proposed for computing the disjoint dominating sets. First, disjoint sets are formed by coloring all nodes, using the sequential coloring algorithm. Then, each non-dominating set is considered in an increasing color number and transformed into a dominating set by recoloring a smallest number of higher-color vertices. When this process ends and no more dominating sets can be formed, the remaining nodes are added to the sets where they have the greatest contribution in covering parts of the uncovered given area. Simulations have shown that the number of sets computed is between 1.5 and 2 times greater than by using the algorithm in [19], with lapses in area coverage less than 5%, on average.

Another energy-efficient node-scheduling-based coverage mechanism is proposed by Tian and Georganas in [20]. The protocol proposed is distributed and localized. Power savings are obtained both by scheduling the sensor nodes activity as well as by considering an adjustable sensing range. The off-duty *eligibility rule* determines whether

a node's sensing area is included in its neighbors' sensing area. Solutions for determining whether a node's coverage can be sponsored by its neighbors (sponsored coverage calculation) is provided for several cases: when nodes have the same sensing range and know their location, when nodes have the same sensing range and can obtain neighboring node's directional information, or in particular scenarios when nodes have different sensing ranges. The node scheduling scheme is divided into rounds, where each round has a self-scheduling phase followed by a sensing phase. In the self-scheduling phase, the nodes investigate the off-duty eligibility rule. Eligible nodes turn off their communication and sensing units, while all other nodes will perform sensing tasks in the sensing phase. In order to obtain neighboring information, each node broadcasts a position advertisement message at the beginning of each round. This message contains the node ID and node location. If the off-duty eligibility rule is tested simultaneously by neighboring nodes, a node and its sponsor may decide to turn off simultaneously, triggering the occurrence of *blind points*. To avoid this, a back-off scheme is used, where every node starts the evaluation rule after a random time, and then broadcasts a status advertisement message to announce if it is available for turning off. Before turning off, a node waits another T_w time to listen for neighboring nodes update. This work does not specify synchronization mechanisms in detail. It is implemented as an extension of the data gathering LEACH protocol [8], and simulation results show an increase of 1.7 on average in system lifetime.

A probing-based, node-scheduling solution for the energy-efficient coverage problem is proposed in [25] by Ye et al. Here, all sensors are characterized by the same sensing range, and coverage is seen as the ratio between the area under monitoring and total size of the network field. The off-duty eligibility rule is based on a probing mechanism. Basically, a sensor broadcasts a probing message PRB within a probing range γ. Any working node that hears this message responds with a *PRB_RPY*. If at least one reply is received, the node enters the sleep mode. Probing range is selected based on the desired working node density (number of sensors per unit area) or based on the desired coverage redundancy, whereas the wake-up time is based on the tolerable sensing intermittence. This protocol is distributed, localized, and has low complexity but still does not preserve the original coverage area.

3.2. Energy-efficient connected coverage

An important issue in WASNs is connectivity. A network is connected if any active node can communicate with any other active node, possibly using intermediate nodes as relays. Once the sensors are deployed, they organize into a network that must be connected so that the information collected by sensor nodes can be relayed back to data sinks or controllers. An important, frequently addressed objective is to determine a minimal number of working sensors required to maintain the initial coverage area as well as connectivity. Selecting a minimal set of working nodes reduces power consumption and prolongs network lifetime. Next we will present several connected coverage mechanisms.

An important, but intuitive result was proved by Zhang and Hou [26], which states that if the communication range R_c is at least twice the sensing range R_s, a complete coverage of a convex area implies connectivity of the working nodes. If the communication range set up is too large, radio communication may be subject to excessive interference. Therefore, if the communication range can be adjusted, a good approach to assure connectivity is to set transmission range as twice the sensing range. Two nodes are neighbors if they have overlapping sensing areas. By intuition, when $R_c \geq 2R_s$, two neighbors are within their communication ranges, as shown in Fig. 2. Based on this result, Zhang and Hou [26] further discussed the case $R_c \geq R_s$. An important observation is that an area is completely covered if there are at least two disks that intersect and all crossings are covered. Here, a disk refers to a node's sensing area, and a crossing is an intersection point of the circle boundaries of two disks. In the ideal case, in which node density is sufficiently high, the full coverage can be obtained by optimally placing the subset of working nodes at the vertices of regular hexagonal plane tiling. Based on these results, authors proposed a distributed, localized algorithm, called optimal geographical density control (OGDC). At any time, a node can be in one of the three states: UNDECIDED, ON and OFF. The algorithm runs in rounds, and at the beginning of each round a set of one or more starting nodes are selected as working nodes. After a back-off time, a starting node broadcasts a power-on message and changes its state to ON. The power-on message contains: (1) the position of the sender and (2) the direction along which a working node should be located. The direction indicated by the power-on message of a starting node is randomly distributed. Having starting nodes randomly selected at the beginning of each round ensures uniform power consumption across the network. Also, the backoff mechanism avoids packet collisions.
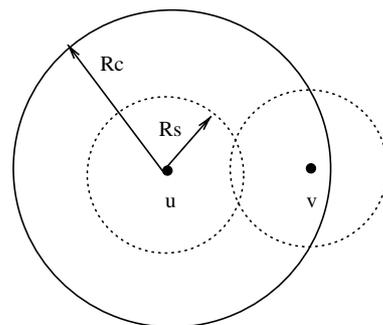
Fig. 2. Two sensors, *u* and *v*, with overlapping sensing areas can directly communicate with each other if $R_c \geq 2R_s$.

At the beginning of each round, all nodes are UNDECIDED and will change either to ON or OFF state until the beginning of the next round. This decision is based on the power-on messages received. Every node keeps a list with neighbor information. When a node receives a power-on message, it checks whether its neighbors cover its sensing area, and if so, it will change to OFF state. A node decides to change into the ON state if it is the closest node to the optimal location of an ideal working node selected to cover the crossing points of the coverage areas of two working neighbors. NS-2 based simulation shows good results in terms of percentage of coverage, number of working nodes and system lifetime.

Some applications may require different degrees of coverage while still maintaining working node connectivity. We say that a network has a coverage degree k (k-coverage) if every location is within the sensing range of at least k sensors. Networks with a higher coverage degree can obtain higher sensing accuracy and be more robust to sensor failure. Wang et al. [21] generalized the result in [26] by showing that, when the communication range R_c is at least twice the sensing range R_s, a k-covered network will result in a k-connected network. A k-connected network has the property that removing any $k-1$ nodes will still maintain the network connectivity. The following discussion addresses the case when $R_c \geq 2R_s$. To define the k-coverage eligibility mechanism, the problem of determining the coverage degree of a region is reduced to a simpler problem of determining the coverage degrees of all the intersection points. Given a coverage region A, a point p is called an *intersection point* if: (1) p is an intersection point of the sensing cycles of any two nodes u and v, e.g. $p \in u \cup v$, and (2) for any node v, $p \in v \cap A$ and $|pv| = R_s$, where R_s is the sensing range. The authors proved that a convex region is k-covered if it contains intersection points and all these intersection points are k-covered. Based on this, a sensor is ineligible to turn active if all the intersection points inside its sensing circle are at least k-covered.

Wang et al. proposed the coverage configuration protocol (CCP) [21] that can dynamically configure the network to provide different coverage degrees requested by applications. To facilitate the computation of intersection points, every node maintains a table with neighbor information (location, status: active/inactive) and periodically broadcasts a HELLO beacon with its current location and status. A node can be in one of the three states: SLEEP, LISTEN and ACTIVE. All nodes start in the SLEEP state for a random time. When a node wakes up, it enters LISTEN state, and based on the outcome of the eligibility rule over a time interval, it will enter either SLEEP or ACTIVE state. Once a node is in the ACTIVE state, it will re-evaluate the coverage eligibility every time it receives a HELLO message and decide whether to go into the SLEEP state or remain in the ACTIVE state.

For the case when $R_c < 2R_s$, CCP does not guarantee network connectivity. The solution adopted in [21] is to integrate CCP with SPAN [4] to provide both sensing coverage and network connectivity. SPAN is a distributed algorithm similar to Wu and Li's marking process [22], that conserves energy by turning off unnecessary nodes while maintaining connectivity. The combined eligibility rule is as follows: (1) an inactive node goes into the active state if it satisfies the eligibility rules of SPAN and CCP, and (2) an active node withdraws if it satisfies neither the eligibility rule of SPAN or CCP. With this combined mechanism we can obtain k-coverage through CCP and 1-connectivity through SPAN. The algorithm was implemented and tested using NS-2 and showed good performance results in terms of coverage, active nodes and system lifetime.

Carle and Simplot [3] propose another mechanism for energy-efficient connected area coverage for the case when all sensor nodes have the same sensing range and the communication range equals the sensing range. The goal of the algorithm is to select an area-dominating set of nodes of minimum cardinality, such that the selected set covers the given area. The main idea is to use one of the existing protocols for building a connected dominating set (e.g. Dai and Wu's algorithm in [5]) but instead of providing the node coverage to assure the area coverage. Once a node has decided its status (active or sleeping) for the next round, it transmits a message to its neighbors. The message sent is referred to as positive or negative advertising, depending on whether the node has decided to be active or in the sleep mode, respectively. Each node sets its priority depending on the remaining battery life and employs a backoff mechanism, such that the nodes with larger energy resources decide their status first. The protocol run by a node u is as follows (1) node u determine whether its monitoring area is already covered by its neighbors, based on the positive or negative advertising messages. If the scheme by Tian and Georganas [20] is used for determining whether the neighbor set covers u's monitoring area, then each node needs to know its neighbors' locations; (2) at the end of the backoff interval, node u computes a subgraph of its one-hop active neighbors; (3) if the subgraph is connected and fully covers u's area, then node u will be in the sleep mode, otherwise it will be in the active mode during the next round. As this algorithm follows the steps in [5], the resulting area-dominating set is connected.

4. Energy-efficient point coverage

In the point coverage problem, the objective is to cover a set of points. Fig. 1(b) shows an example of a set of sensors randomly deployed to cover a set of points (small square nodes). The connected black nodes form the set of active sensors, the result of a scheduling mechanism. The two important properties of energy-efficiency and connectivity are also explored by the following two point coverage mechanisms, presented in Sections 4.1 and 4.2.

4.1. Energy-efficient coverage

Cardei and Du [2] address the point coverage problem in which a limited number of points (targets) with known locations need to be monitored. A large number of sensors are dispersed randomly in close proximity to the targets and send the monitored information to a central processing node. The requirement is that every target must be monitored at all times by at least one sensor, assuming that every sensor is able to monitor all targets within its sensing range.

One method for extending the sensor network lifetime through energy resource preservation, is the division of the set of sensors into disjoint sets such that every set completely covers all targets. These disjoint sets are activated successively, such that at any moment in time only one set is active. As all targets are monitored by every sensor set, the goal of this approach is to determine a maximum number of disjoint sets, so that the time interval between two activations for any given sensor is longer. By decreasing the fraction of time a sensor is active, the overall time until power runs out for all sensors is increased, and the application lifetime is extended proportionally by a factor equal to the number of disjoint sets.

A solution for this application is proposed in [2], where the disjoint sets are modeled as disjoint set covers, such that every cover completely monitors all the target points. Cardei and Du [2] prove that the disjoint set coverage problem is NP-complete and any polynomial-time approximation algorithm has a lower bound of 2. The disjoint set cover problem is reduced to a maximum flow problem, which is modeled as a mixed integer programming. Simulation shows better results in terms of numbers of disjoint set covers computed, compared with most-constrained least-constraining algorithm [19], when every target is modeled as a field.

4.2. Node coverage as approximation

When a large and dense sensor network is randomly deployed for area monitoring, the area coverage can be approximated by the coverage of the sensor locations. That is, based on the assumption of a large and dense population of sensors, by covering each sensor location we can approximate the coverage of each point in the given area. One method to assure coverage and connectivity is to design the set of active sensors as a connected dominating set (CDS). A distributed and localized protocol for constructing the CDS was proposed by Wu and Li, using the *marking process* in [22]. A node is a coverage node if there are two neighbors that are not connected (i.e. not within the transmission range of each other). Coverage nodes (also called gateway nodes) form a CDS. A pruning process can be used to reduce the size of coverage node set while keeping the CDS property. Dai and Wu [5] provide a generalized pruning rule called *pruning rule k*. Basically,

a coverage node can be withdrawn if its neighbor set can be collectively covered by those of k coverage nodes. In addition, these k coverage nodes have higher priority and are connected. Pruning Rule k ensures a constant approximation ratio. The CDS derived from the marking process with Rule k can be locally maintained, when sensors switch-on/off.

Wu et al. [23] also discuss the energy-efficient dominating set coverage approach. In general, nodes in the connected dominating set consume more energy in order to handle various bypass traffic than nodes outside the set. To prolong the life span of each node, and hence, the network by balancing the energy consumption in the network, nodes should be alternated in being chosen to form a connected dominating set. A set of power-aware pruning rules is proposed, where coverage nodes are selected based on their energy levels. Simulation results in [23] show that the modified power-aware marking process outperforms several existing approaches in terms of life span of the network.

The node coverage problem can be related to the broadcasting problem, where a small set of forwarding nodes is selected [24]. Forwarding set selection in broadcasting is similar to the point coverage problem, where both try to find a small coverage set. Note that directed diffusion [11] also uses this platform to collect information through broadcasting. As the interest is propagated through the network, sensor nodes set up reverse gradients to the sink in a decentralized way. The difference is that in the directed diffusion, all sensors forward the data. One difference between node coverage and area coverage is that neighbor set information is sufficient for node coverage, while in area coverage, geometric/directional information is needed.

5. Conclusion

In this article we described recent energy-efficient coverage problems proposed in literature, their formulations and assumptions as well as solutions proposed. Sensor coverage is an important element for QoS in applications with WASNs. Coverage is, in general, associated with energy-efficiency and network connectivity, two important properties of a WASN. To accommodate a large WASN with limited resources and a dynamic topology, coverage control algorithms and protocols perform best if they are distributed and localized.

Various interesting formulations for sensor coverage have been recently proposed in literature. Scheduling sensor nodes to alternate between sleep and active mode is an important method to conserve energy resources. Such mechanisms that efficiently organize or schedule the sensor activity after deployment are very efficient and have a direct impact on prolonging the network lifetime. Most recent works on the sensor coverage problem are still limited to theoretical study, where only centralized solutions are given. In future research, more and more work will be

focused on distributed and localized solutions for practical deployment.

Acknowledgements

References

[1] M. Cardei, D. MacCallum, X. Cheng, M. Min, X. Jia, D. Li, D.-Z. Du, Wireless sensor networks with energy efficient organization, Journal of Interconnection Networks 3 (3–4) (2002) 213–229.

[2] M. Cardei, D.-Z. Du, Improving wireless sensor network lifetime through power aware organization, ACM Wireless Networks, 11 (3) 2005.

[3] J. Carle, D. Simplot, Energy efficient area monitoring by sensor networks, IEEE Computer 37 (2) (2004) 40–46.

[4] B. Chen, K. Jamieson, H. Balakrishnan, R. Morris, Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks, ACM/IEEE International Conference on Mobile Computing and Networking 2001; 85–96.

[5] F. Dai, J. Wu, Distributed dominant pruning in ad hoc wireless networks, Proceedings of IEEE International Conference on Communications (CD-ROM) 2003.

[6] D.W. Gage, Command control for many-robot systems, Proceedings of the Nineteenth Annual AUVS Technical Symposium 1992; 22–24.

[7] W.W. Gregg, W.E. Esaias, G.C. Feldman, R. Frouin, S.B. Hooker, C.R. McClain, R.H. Woodward, Coverage opportunities for global ocean color in a multimission era, IEEE Transactions on Geosience and Remote Sensing 5 (1998) 1620–1627.

[8] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocols for wireless microsensor networks, Proceedings of HICSS (CD-ROM) 2000;.

[9] A. Howard, M.J. Mataric, G.S. Sukhatme, Mobile sensor network deployment using potential fields: a distributed, scalable solution to the area coverage problem, Proceedings of the Sixth International Symposium on Distributed Autonomous Robotic System 2002; 299–308.

[10] G.T. Huang, Casting the wireless sensor net, Technology Review 2003; 50–56.

[11] C. Intanagonwiwat, R. Govindan, D. Estrin, Directed diffusion: a scalable and robust communication paradigm for sensor networks, Proceedings of ACM MobiCom 2000; 56–67.

[12] K. Kar, S. Banerjee, Node placement for connected coverage in sensor networks, Proceedings of WiOpt : Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks 2003.

[13] M. Marengoni, B.A. Draper, A. Hanson, R. Sitaraman, A system to place observers on a polyhedral terrain in polynomial time, Image and Vision Computing 18 (2000) 773–780.

[14] S. Meguerdichian, F. Koushanfar, M. Potkonjak, M. Srivastava, Coverage Problems in Wireless Ad-Hoc Sensor Networks, IEEE Infocom 2001; 1380–1387.

[15] S. Meguerdichian, F. Koushanfar, G. Qu, M. Potkonjak, Exposure in wireless ad hoc sensor networks, Proceedings of the Seventh Annual International Conference on Mobile Computing and Networking 2001; 139–150.

[16] S. Megerian, M. Potkonjak, in: J.G. Proakis (Ed.), Wireless Sensor Networks, Wiley Encyclopedia of Telecommunications, New York, 2002.

[17] V. Raghunathan, C. Schurgers, S. Park, M.B. Srivastava, Energy-aware wireless microsensor networks, IEEE Signal Processing Magazine 19 (2002) 40–50.

[18] J. O'Rourke, Art Gallery Theorems and Algorithms, Oxford University Press, Oxford, 1987.

[19] S. Slijepcevic, M. Potkonjak, Power efficient organization of wireless sensor networks, Proceedings of IEEE International Conference on Communications 2 (2001) 472–476.

[20] D. Tian, N.D. Georganas, A Coverage-Preserving Node Scheduling Scheme for Large Wireless Sensor Networks, Proceedings of the First ACM Workshop on Wireless Sensor Networks and Applications 2002.

[21] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, C.D. Gill, Integrated coverage and connectivity configuration in wireless sensor networks, accepted to the First ACM Conference on Embedded Networked Sensor Systems (2003).

[22] J. Wu, H. Li, On calculating connected dominating set for efficient routing in ad hoc wireless networks, Proceedings of the Third International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications 1999; 7–14.

[23] J. Wu, F. Dai, M. Gao, I. Stojmenovic, On calculating power-aware connected dominating sets for efficient routing in ad hoc wireless networks, Journal of Communications and Networks 1 (2002) 1–12.

[24] J. Wu, F. Dai, Broadcasting in ad hoc networks based on self-pruning, Proceedings of the 22nd Annual Joint Conference of IEEE Communication and Computer Society (CD-ROM) 2003.

[25] F. Ye, G. Zhong, S. Lu, L. Zhang, Energy efficient robust sensing coverage in large sensor networks, Technical Report UCLA (2002).

[26] H. Zhang, J.C. Hou, Maintaining Sensing Coverage and Connectivity in Large Sensor Networks, Technical Report UIUC, UIUCDCS-R-2003-2351 (2003).