

Efficient Coverage and Connectivity in Wireless Sensor Networks

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Abstract—This paper surveys several protocols for energy conservation in wireless sensor networks which preserve a certain degree of coverage and connectivity of the initial network. The idea is to schedule redundant nodes to sleep mode while the active nodes provide continuous monitoring. Thus minimizing the number of active nodes determines the increase of network lifetime.

There are two research directions for conserving energy in wireless sensor networks. Early work focused to conserve energy while preserving only coverage or connectivity of the initial network. On the other hand, recent work focused to conserve energy while preserving both coverage and connectivity at the same time. As fully functional sensor networks (which can perform sensing and can communicate with other nodes) are a fundamental requirement, the second direction is preferable.

Most of the approaches use particular relationships between the sensing range and the communication range to simplify the integrated coverage and connectivity problem to a traditional coverage problem. However, as these particular relationships do not hold always other mathematical theorems have been introduced to guarantee coverage and connectivity preservation in more generic situations.

I. INTRODUCTION

In this paper I survey several protocols for wireless sensor networks which conserve energy consumption by putting redundant nodes into sleep mode while maintaining different levels of coverage and connectivity. I start with presenting solutions that guarantee only coverage preservation. Then I continue with solutions that guarantee both coverage and connectivity preservation at the same time. The emphasize will be put on the second ones.

Energy conservation is a primarily concern in wireless sensor networks which have to operate during long periods of time based on battery power. For instance, habitat / battlefield monitoring may require continuous operation of at least several months. Moreover, in the second case it might be difficult to replace batteries

when these are drained out because of the inaccessible areas where these are deployed (usually sensor nodes are deployed randomly from airplanes). Recent research showed that significant energy savings can be achieved by scheduling node duty cycles in high density sensor networks. Specifically, some nodes are scheduled to sleep while the remaining ones provide continuous monitoring. The main issue here is how to minimize the number of active nodes in order to maximize the network lifetime and in the same time to ensure the required quality of service for applications.

Coverage and connectivity are the fundamental requirements in wireless sensor networks and can be considered the metrics of interest when targeting quality of service for applications. Coverage is the area or the number of targets that can be monitored by a sensor. An area / target can be monitored by several sensors in which case it has a higher coverage degree. The coverage degree is determined by applications and the number of faults that has to be tolerated. On the other hand, connectivity ensures that sensor nodes can communicate with each other in order to aggregate data reports hop-by-hop to the base stations (sinks). The connectivity level also determines the communication robustness in a sensor network.

Most of the energy conservation protocols ensure only one of the fundamental requirements of the wireless sensor networks, either sensing coverage or network connectivity [1]. In other words, some protocols ensure coverage preservation of the original sensor network without any connectivity guarantees between nodes, while other protocols ensure connectivity preservation of the original network, without any coverage guarantees. A lot of work focused on the coverage problem. In [2] linear programming techniques are used in order to select the minimal set of nodes required for preserving coverage. In [3] a heuristic that selects mutually exclusive sets of nodes that cover the entire monitored area is introduced. Based on this work, Cardei et al. [4] propose another method to extend sensor network lifetime by organizing

sensors into a maximal number of set covers which are successively activated. In contrast to [3] sensors are allowed to participate in multiple sets. Heuristics and linear algebra are used to compute the sets. Tian et al. [5] propose a node scheduling technique which turns off redundant nodes while maintaining the original coverage. The eligibility-rule to turn off nodes is based on the sponsored coverage calculation model. However, none of these works considered to maintain in the same time the level of connectivity. On the other hand, several other protocols like: ASCENT [6], SPAN [7] or GAF [8] maintain connectivity between sensor nodes, without any concerns regarding coverage. As already stated, ensuring only coverage or connectivity preservation is not sufficient for a fully functional sensor network.

Several other protocols [1], [9], [10], [11] conserve battery power while ensuring both coverage and connectivity preservation. Different assumptions and solutions are considered in order to maintain coverage and connectivity. In [1], [9] is proved that for a communication range at least double of the sensing range the connectivity requirement is implicitly ensured by network coverage. The work of Tian et al. [10] is built incrementally on the previous ones, and proves that "the communication range is twice of the sensing range" is the sufficient condition and the tight bound which ensures that coverage preservation implies connectivity among nodes if the original network is connected. A set of novel theorems that generalize the previous findings are introduced and proved by Huang et al. in [11]. Another interesting approach is PEAS [12], a lightweight solution that has a high degree of adaptivity.

This paper rest of the paper is organized as follows. Section II introduces the theoretical foundation: specifically, the definitions and the notations used in the next sections of the paper. Section III presents several solutions for the coverage problem when taken separately. Section IV presents and analyzes in detail solutions which achieve both coverage and connectivity preservation at the same time while maintaining a low number of active nodes. Section V concludes the paper.

II. THEORETICAL FOUNDATIONS ON COVERAGE AND CONNECTIVITY

In this section I describe briefly the definitions and the notations used in the next sections of the paper, as presented in [1], [11].

- **Coverage degree:** A convex region A has a coverage degree of K or is K -covered if every location inside A is covered by at least K nodes. I should emphasize here that a network with a higher degree of coverage has higher sensing accuracy and thus is more robust to failures.
 - **Coverage configuration problem or Coverage problem:** For a given region A , a set of sensors that L -cover A , and a coverage degree K , specified by application, we have to maximize the number of sleeping nodes under the constrained that the remaining nodes can ensure that A is K -covered ($L \geq K$).
 - **Connectivity:** Two nodes u and v can directly communicate with each other if their Euclidian distance is less than a communication range R_c . Specifically, $uv < R_c$.
 - **Connectivity degree:** A sensor network is said to be 1 -connected if there is at least one path between any two sensors. Moreover, the sensor network is said to be k -connected if there are at least k disjoint paths between any two sensors.
 - **Integrated coverage and connectivity problem or Integrated problem:** For a given region A and a coverage degree of K the goal is to maximize the number of nodes that can be scheduled to sleep under the constrained that the remaining nodes guarantee the following two conditions: i) A is at least K covered and ii) all active nodes are connected.
- Another set of definitions, required to understand the theorems presented in Subsection IV-A are here described (as presented in [11]):
- Consider that we have a set of n sensor $S = s_1, s_2, \dots, s_n$ located inside a region A . Each sensor is located at a certain position inside A and has a sensing range R_s and a communication range R_c . We make no assumptions about the relationships of R_s and R_c .
- For two given sensor s_i and s_j we say that a point p on the perimeter of (on the sensing range of) s_i is *perimeter-covered* by s_j if p is within the sensing range of s_j . A point p on the perimeter of s_i is *k-perimeter covered* if it is perimeter covered by at least k sensors other than itself. Finally, the sensor s_i is *k-perimeter-covered* if all points on the perimeter of s_i are perimeter-covered by at least k sensors other than itself.
 - For a given sensor s_i we define the *neighboring set of s_i* by $N(i)$ which is the set of sensors each of whose sensing regions overlaps with the sensing region of s_i .
 - Consider a given sensor s_i . We say that s_i

is *k*-direct-perimeter-covered (*k*-DPC) if s_i is *k*-perimeter covered and s_i has a link to each node in $N(i)$. In a similar way, we say that s_i is *multi-hop-neighbor-perimeter-covered* (*k*-MPC) if s_i is *k*-perimeter-covered and s_i has a direct or multi-hop link to each node in $N(i)$.

- $DN(i)$ is the direct neighboring set of s_i and represents the set of sensors that have a communication link to s_i and whose sensing region intersects with s_i 's sensor region. In a similar manner, the $MN(i)$ or the multi-hop neighboring set of s_i is the set of sensors that has a single or multi-hop path to s_i and whose sensing range intersects with s_i 's.
- Consider a given sensor s_i . We say that s_i is *k*-loose-direct-neighbor-perimeter-covered (*k*-LDPC) if s_i is *k*-perimeter-covered by and only by nodes in $DN(i)$. In a similar way, s_i is *k*-loose-multi-hop-neighbor-perimeter-covered (*k*-LMPC) if s_i is *k*-perimeter-covered by and only by nodes in $MN(i)$.

III. EFFICIENT COVERAGE

This Section presents several solutions for the efficient coverage problem. All of these target to minimize the number of active nodes while ensuring the required QoS guarantees for applications. Most of the presented approaches maximize the number of node sets that can cover the entire monitoring area and schedule each set in a round-robin fashion. After each individual solution is briefly presented, an analysis will follow.

a) SET K-COVER Problem: Slijepcevic et al. introduce in [3] the SET K-COVER problem. The problem is to organize mutually exclusive sensor nodes into a number of covers or sets each of which can fully cover the monitoring area A . The activity duration for each cover is the same and thus the energy consumption is uniform among nodes. As the lifetime of the network is direct proportional with the number of allocated covers, the goal is to maximize the number of covers. They prove that the problem is NP complete and they use an heuristic based on most constrained-minimally constraining paradigm in order to solve it. In the first phase they count how many different nodes cover different parts of the monitored area, while in the second phase they allocate sensor nodes into mutually independent sets. When selecting sensors, priority is given to sensors that cover a high number of uncovered sets, that cover sparsely covered fields and that do not cover redundantly. The theoretical complexity of the heuristic is $O(N^2)$, where N is the number of deployed sensors. Their simulations compare the proposed heuristic with a simulated annealing based heuristic and show that the number of

cover sets obtained is larger when most constrained-minimally constraining heuristic is used. The run-time execution is much better for the proposed solution. For the case when sensor nodes are uniformly deployed on the area A , they show a significant improvement in the number of set covers.

b) Low Power Coverage: Meguerdichian et al. introduce in [2] the ILP¹ formulations for the Minimum 0-1 Cover, Minimal Cover with Sensor Field Intensity and Balanced Operation Scheduling problems. The Minimum 0-1 Cover tries to find the minimum number of sensors that can cover the entire monitoring area A while the Minimal Cover with Sensor Field Intensity tries to achieve the same goal with the guarantee that the sensor field intensity for each region of A is above a user specified threshold value (They consider that the coverage intensity for a region decreases as the distance from the sensor node increases). Finally, in Balanced Operation Scheduling the goal is to produce a user specified number of subsets that can cover the region A such that each sensor is active in as few sets as possible. They solve the ILP instances by using LP-SOLVE, a Mixed Integer Linear Program solver. What is interesting to notice is that even their simulation results show acceptable fairness regarding the time intervals each sensor is active, their scheduling mechanism cannot guarantee the straight balance among the sensor nodes; inevitable some nodes will be scheduled more in sparse regions.

c) Target Coverage: Cardei et al. introduce in [4] an efficient target coverage mechanism for sensor networks. The idea is to extend the network lifetime by organizing sensors into the maximal number of set covers. These set covers are activated successively such that at any given time only a set is active. The nodes from the active set will be in the active state while all the others will be in the sleep state. A key difference between this approach and [3] is that the sensor nodes can participate in multiple sets (the covers do not contain mutually exclusive nodes). The single restriction is that the sum of all time weights associated with the sets a node belongs to has to be 1. Thus, in a complete cycle each node consume the same amount of energy. Another difference is that this approach covers a set of targets, not an area as we have seen in previous works. They formalize the Maximum Set Covers (MSC) problem and they prove that is NP-complete. In order to find the solutions two heuristics are used: a linear programming (LP) heuristic and a greedy heuristic. The

¹Integer Linear Programming is linear programming with the additional constraint that the solution variables are integers. Another difference is that solving an ILP instance is NP-hard.

TABLE I
EFFICIENT COVERAGE APPROACHES

Approach	Problem	Full coverage	Scheduling	Observations
K-COVER [3]	Maximize # of covers	YES	Balanced	-Problem is NPC -Most constrained, minimally constraining covering heuristic -Centralized
Low-power coverage [2]	Minimal Cover Balanced Scheduling	YES	Balanced	-Linear Program Solver -Centralized
Target coverage [4]	Maximum Set Covers	YES	Overall balanced	-Problem is NPC -LP and Greedy heuristics -Centralized -Degree of redundancy
Preserving coverage [5]	Node Scheduling Scheme	YES	Overall balanced	-Distributed & localized -Run in rounds, state information -Self configuring -Degree of redundancy

Greedy heuristic has a lower complexity than LP and thus a lower execution time. The evaluation confirms that Greedy performs slightly better and that is more scalable for large sensor networks. They also show that for a specified number of targets the network lifetime increases with the increase of the number of sensors and the increase of sensing range. On the other hand, by using a constant number of sensors and sensing ranges they observe that the lifetime decreases with the increase of the number of targets.

d) Preserving Coverage: Tian et al. present in [5] a distributed and localized node scheduling algorithm capable to minimize the number of active nodes while preserving area coverage. The scheduling runs in rounds. Each round starts with a self-scheduling phase in which each node investigate its off-duty eligibility. Specifically, if a node's sensing range is sufficiently covered by its neighbors is eligible to turn off and save energy. Non-eligible nodes perform sensing during the second phase of the algorithm. Each node needs to know the position of its neighbors to calculate its off-duty eligibility. In the first phase each node advertises its position and waits for neighboring nodes' position information. Then it computes its off-duty eligibility. To ensure that not all of the eligible nodes decide to turn themselves off a backoff scheme combined with a ready-to-off timer are used. In experimental evaluation they show that the number of off-duty nodes decreases with the increase of node density and the sensing range. However, the number of active nodes also increases with the node density increase when the deployed area and sensing range is fixed. They also combined this scheduling scheme with LEACH [13] data gathering protocol in order to analyze the energy efficiency. Their simulations show that the modified protocol is more effective and can extend the

system lifetime.

A. Analysis

As it was already seen almost all the approaches are targeting to optimize the number of sets of nodes that can monitor the entire deployment area without affecting the QoS guarantees required by applications. They are based on centralized schemes and are using heuristics to find solutions for the problem. Each set of nodes is scheduled at a given time and the time intervals each node is active are balanced. As in each cycle there are inactive nodes, the network lifetime will be increased proportional with the number of node covers. [5] is the exception that does not follow all of these general properties. Specifically, [5] is a distributed approach enhanced with self-configuring capabilities. This solution is the most realistic one in my opinion as it can be scalable in high density networks. In addition it ensures the level of coverage with a certain level of redundancy. [4] also improves the algorithm proposed in [3] as it maximize the number of set covers without the restriction that sets should contain only mutually exclusive nodes. This determines a larger number of possible set covers as compared with [3]. [4] has another difference: it targets to cover only a set of discrete nodes, not an entire area as the other solutions. Table I summarize the characteristics of each approach.

IV. INTEGRATED COVERAGE AND CONNECTIVITY

This Section introduces several approaches that try to conserve energy consumption in wireless sensor networks while ensuring a minimum degree of coverage and connectivity. I start with introducing the theorems that simplify the integrated coverage and connectivity problem to a coverage problem when the communication

range is at least twice the sensing range and then I continue with presenting more generic theorems that can be always applied. Next I present protocols that use these theorems to solve the integrated coverage and connectivity problem. At the end I analyze and compare these protocols.

A. Relationships between Coverage and Connectivity

In [1] Wang et al. introduce a sufficient condition that guarantees implicit connectivity. More exactly, they prove that in a sensor network where the communication range is at least twice the sensing range, the connectivity is implicitly ensured if the network is covered. They introduce and prove the following theorems:

Theorem 1. "For a set of sensor that at least 1-cover a convex region A , the communication graph is connected if $R_c \geq 2R_s$." [1]

Theorem 2. "A set of nodes that K -cover a convex region A forms a K -connected communication graph if $R_c \geq 2R_s$." [1]

Theorem 1 ensures that for a communication range of at least twice the sensing range, 1-coverage guarantees 1-connectivity. Specifically, for $R_c \geq 2R_s$ we can be concerned only with preserving coverage in the scheduling mechanism, as the connectivity will be implicitly satisfied. Theorem 2 generalize Theorem 1 and provides K -connectivity for an initial sensor network that is K -covered.

In [10] Tian et al. extend the relationships between coverage and communication presented above. Basically, they introduce and prove the following theorems:

Theorem 3. "When $R_c \geq 2R_s$ and the system sensing coverage is completely preserved after node scheduling, if a network graph $G(V, E)$ is originally connected, then the induced subgraph $G(V_{active})$ must be connected." [10]

Theorem 4. " $R_c \geq R_s$ is the sufficient condition and the tight lower bound to ensure that complete sensing coverage preservation implies network connectivity among active nodes in an original connected network graph." [10]

Theorem 3 can be better understood from Figure 1. As it can be seen the sensing field is divided into 4 subfields, each subfield completely covered by a subset of nodes. In the middle of the sensing fields two narrow gaps that cannot be monitored by any node exist. The initial network is connected and as already stated not fully covered. In this case, as a result of a scheduling

algorithm which puts into sleep mode several active nodes, Theorem 1 cannot ensure connectivity for the resulting network. It can ensure only that the nodes within each subset are connected. However, Theorem 3 is more powerful and provides connectivity maintenance for all the nodes within the field even in this situation.

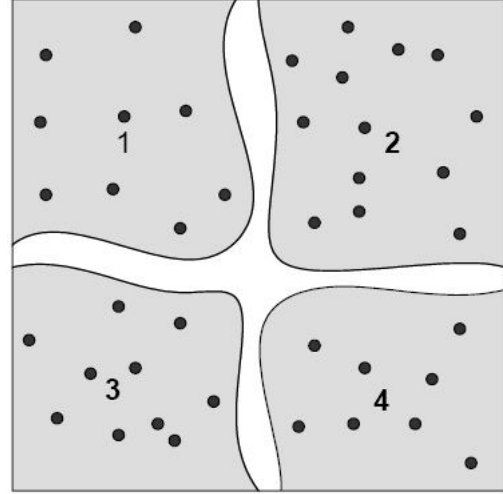


Fig. 1. Difference between Theorem 1 and Theorem 3. [10]

Theorem 4 lightly extends the relationship between connectivity and coverage introduced in Theorem 1 and enable us to focus only on coverage problem when both coverage and connectivity have to be satisfied.

More general theorems which are not based on any particular relationships between R_s and R_c are introduced in [11]. In order to understand these theorems please review the definitions presented in Section II if necessary:

Theorem 5. "A sensor is k -covered and 1-connected if and only if each sensor is k -MPC." [11]

Theorem 6. "A sensor network is k -covered and k -connected if each sensor is k -DPC." [11]

As we can see Theorem 5 guarantees 1-connectivity and Theorem 6 guarantee k -connectivity. Moreover, Theorem 6 is stronger than Theorem 1 which is only a particular case of the first one. In other words, what can be determined by Theorem 1 can also be determined by Theorem 6. In addition, when the condition $R_c \geq R_s$ does not hold, Theorem 6 may still work while Theorem 1 cannot be applied. For instance, the sensor network presented in Figure 2 is determined to be 1-covered and 1-connected even that some sensors' communication range is less than twice of the sensing ranges.

Finally, two other theorems introduced in [11] which worth to be mentioned are here presented:

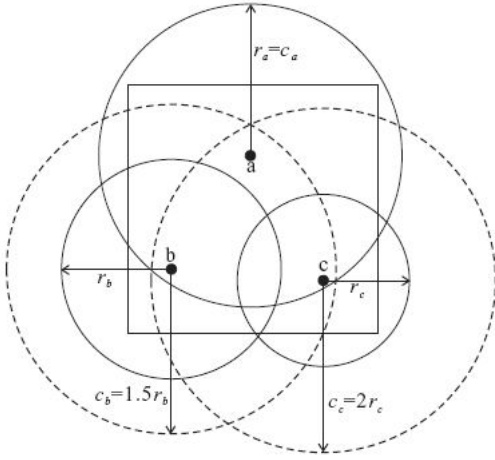


Fig. 2. An example comparing Theorem 6 with other results from the literature. Solid circles are sensors' sensing ranges and dotted circles are communication ranges. [11]

Theorem 7. "A sensor network can be decomposed into a number of connected components each of which k -covers A if and only if each sensor is k -LMPC." [11]

Theorem 8. "A sensor network can be decomposed into a number of k -connected components each of which k -covers A if each sensor is k -LDPC." [11]

As we can observe Theorem 7 and Theorem 8 can only guarantee that the network is k -covered by each of its connected components. These are the looser form for Theorem 5 and Theorem 6 (these converge for $DN(i)=N(i)$ or $MN(i)=N(i)$). An example of two connected components which 1-cover A can be seen in Figure 3.

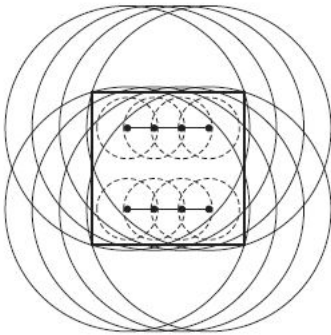


Fig. 3. An example of two connected components each of which covers the square A . [11]

B. Integrated Coverage and Connectivity Approaches

In this sub-section I describe several protocols which conserve energy by scheduling sensor nodes to sleep or

by combining scheduling with power management. Most of these solutions are using the theorems just described in the previous section.

e) **CCP**: : CCP or Coverage Configuration Protocol [1] is one of the first solutions that tries to achieve both coverage and connectivity in a single protocol. For $R_c \geq 2R_s$ it uses Theorem 1 and Theorem 2 to simplify the problem to a commodity coverage problem. For the other case $R_c < 2R_s$ it combines its own protocol with SPAN² [7] to ensure coverage and connectivity.

The eligibility rule of CCP decides if a sensor node has to be active or not according with the actual coverage of its sensing area. If its sensing area is already sufficiently covered by the neighboring nodes, the node can be inactive and enter in the SLEEP mode. A node can be in there states: SLEEP, LISTEN and ACTIVE. In the SLEEP mode a node sleeps to conserve energy. In ACTIVE state the node actively senses the environment and communicates with other sensors. Periodically, each node enters in the LISTEN state to collect HELLO messages from its neighbors and reevaluates its eligibility rule to determine its next state. The network of active nodes adapts dynamically. More exactly, if in a high density area the coverage degree exceeds the requirements, redundant nodes can go in the SLEEP mode while in other cases, when an active sensor run out of energy, sensors that are in the SLEEP state will find themselves eligible to enter the ACTIVE state. Timers are associated with each state and a backoff mechanism is used to avoid collisions among multiple nodes that decide to join or withdraw the ACTIVE state.

CCP is a decentralized protocol which requires location information about all its neighbors in order to check the eligibility rule. For this reason, the neighbor nodes send messages which include their location information and the location information of their own neighbors. This helps to find the node's neighbors even when $R_c < 2R_s$. Other advantages that CCP offers is its configurable coverage degree. So, applications can change the required coverage degree at run-time.

In the experimental results they show that for the same coverage degree CCP uses less than half of the number of nodes used by the Ottawa approach (presented later in this section). As an immediate effect this guarantees a longer network lifetime. They also showed that by combining

²SPAN [7] is a decentralized protocol which conserves energy while maintaining a communication backbone with the set of active nodes. All active nodes are connected through the backbone and all inactive nodes are at least connected directly to an active node. The goal is to maintain a network topology capable to ensure a certain network capacity and delay as the original network. In SPAN a node becomes active or coordinator if it satisfies the eligibility rule, otherwise it remains inactive.

CPP with SPAN, both the system coverage time and the system communication time are approximatively two times greater than the original life time of the network (without any scheduling algorithm). In Figure 4 a)-c) we can see how the combination of CCP and SPAN ensures coverage and connectivity for $R_c/R_s = 1.5$. Small dots are inactive nodes, medium size dots are sink nodes located at the right of the boundary and large dots represent active nodes. The sensing areas are represented by circles. As we can see SPAN does not maintain fully coverage. CCP ensures connectivity for this particular case, however sparse connectivity is ensured in the middle of the network. In the last figure we can see that the combination of CCP with SPAN maintains a better connectivity and thus a better communication performance.

f) **PEAS**: : PEAS [12] uses a similar technique for turning off nodes. However, PEAS design targets a much more hostile environment where: i) node failures are high, ii) the node deployment density is high and iii) due to hardware limitations, sensor nodes cannot run complex protocols. PEAS protocol is simple and consists of two algorithms: Probing Environment, which determines which nodes should work and Adaptive Sleeping, which determines how to adjust dynamically the sensors' sleep times in order to keep a constant wake-up rate. At the beginning all the nodes are sleeping for an exponentially distributed random time. When a node wakes-up, it broadcasts a PROBE message within a certain range R_p . Any working node that receives the message responds with a REPLY. If the initial node receives at least a single REPLY it goes back to sleep, otherwise becomes an active node. Adaptive Sleeping adjusts the wake-ups of sleeping neighbors for each working node to ensure the level of redundancy required by applications.

There are no relationships between sensing and communication ranges specified, nor strong coverage or connectivity guarantees. However, the R_p can be adjusted in order to offer better coverage and connectivity (e.g. smaller values for R_p and much higher values for R_c determine an improved connectivity).

Their evaluation shows the robustness of PEAS and the network lifetime extension which varies linearly with the number of deployed nodes. A performance comparison between PEAS and other energy conserving protocols is done as part of the following approach.

g) **OGDC**: : The Optimal Geographical Density Control algorithm is another solution which minimizes the number of active sensors used to conserve energy while ensuring coverage and connectivity preservation in high density sensor networks. Zhang et al. prove in [9] a similar theorem to Theorem 1 and they apply it to

simplify the integrated connected coverage problem. In addition, they also devise several optimality conditions for covering a region A with the minimum overlap of the covered neighbor areas.

In OGDC a node is in one of the three states: UNDECIDED, ON or OFF. The algorithm runs in rounds. At the beginning of each round all the nodes wake up, set their state to UNDECIDED and participate in selecting the active nodes. A node volunteers to be a starting node with a probability p . After a backoff time the node broadcasts a power-on message to its neighbors and changes its state to ON. This message contains the position of the node and the direction along which the second working node should be located. This direction is randomly generated so ensures a uniform distribution in $[0, 2\pi]$. The nodes will change their state either to ON or OFF based on power-on messages received. Each node maintains a list with its neighbors. After a node receives a power-on message it checks if its sensing area is already covered by its neighbors. If so, it changes its state to OFF. A node changes its state to ON if it is the closest node to an optimal location for a new working node. The usage of backoff timers avoids packet collisions. By the end of the algorithm execution all the nodes set their state to either ON or OFF until the end of the round.

In the experimental evaluation the authors compare OGDC with PEAS [12] and GAF [8] and they show that a reduced number of deployed nodes are required for OGDC to achieve coverage. Moreover, the network lifetime is increased by 1-2 times as compared with PEAS [12] with different probing settings. Figure 5 shows that OGDC uses approximatively half of the working nodes of PEAS and less than half of the working nodes of GAF.

h) **Ottawa Approach**: : After introducing Theorem 3 and Theorem 4 in [10] Tian et al. perform several experiments with their simulator fully described in [5]. Basically, they use the same coverage preserving scheduling algorithm already presented in Section III. The results prove again the connectivity maintenance when the communication range is twice the sensing range.

i) **Sleep and PC**: : Huang et al. combine two mechanisms to increase network lifetime. Specifically, they use a scheduling algorithm which puts some sensors into the sleep mode, and additionally they conserve more energy by reducing the transmission power of sensors. By scheduling they reduce the degree of coverage and by power management they reduce the degree of connectivity. The goal is to conserve as much energy as possible while maintaining the ks-coverage and the kc-

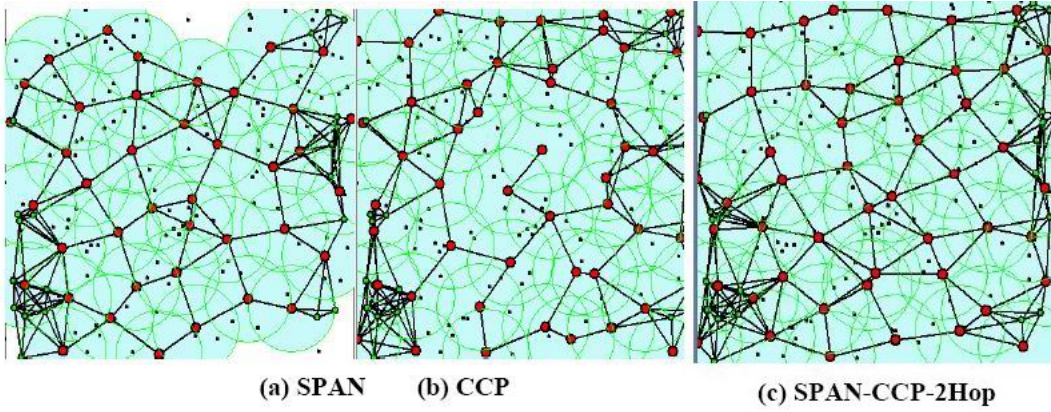


Fig. 4. Coverage and Connectivity for $R_c/R_s=1.5$ [1]

connectivity required by the application. An important difference here is that they do not impose any restrictions on the relationship between R_c and R_s . They use the last 4 theorems presented in Section IV-A which ensure coverage and connectivity preservation for more general cases than the first theorem.

Sleep protocol requires each sensor know the location and the sensing regions of its two hop neighbors that are in the active state. The two-hop neighbor information is obtained from BEACON messages sent by each direct neighbor sensor. This information includes the sensor's location, its sensing range and the actual power setting. Before a sensor can go to sleep a set of steps have to be followed. Basically, the sensor has to ensure that its sensing area is sufficiently covered by neighbor nodes and then has to ask for confirmation from all its neighbors. Otherwise, too many sensor nodes could potentially go to sleep state at the same time. To avoid collisions a backoff mechanism is used.

Power Control protocol reduces the transmission power of sensors in order to save energy. The main idea is to disconnect the direct connection from a sensor node s_x to its farthest direct neighbor s_y with the restriction that the network obtained will maintain a certain level of connectivity. If the level of connectivity is maintained by reducing the transmission power of s_x this action is taken after receiving a confirmation message.

They also provide a simple mechanism to combine the Sleep protocol with the Power Control protocol into a single protocol. Their evaluation for the network lifetime compares the performance of a naive approach, Sleep, Sleep+PC and CCP+SPAN for several ks-coverage degrees and kc-communication degrees. Figure 6 show the most interesting results. a) shows the obtained coverage level and b) shows the network lifetime for ks=2 and kc=1 (the sensing ranges varied between 15-25 units

and the communication range varied between 30-50 units). The conclusion is that the combination Sleep+PC maintains the best fit for the required coverage and connectivity degrees while the other protocols offer too much redundancy. The second conclusion is that Sleep+PC has also encouraging improvements in the network lifetime, superior to CCP+SPAN.

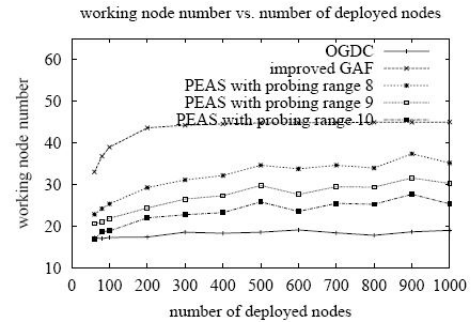


Fig. 5. Number of working nodes versus the number of deployed nodes in a $50 \times 50 \text{ m}^2$ area. [9]

C. Analysis

In this Section I presented several approaches which offer both coverage and connectivity guarantees at the same time. Most of these are based on scheduling algorithms which are limiting the number of active nodes by putting redundant nodes into the sleep mode. Another approach combines scheduling with power management to reduce further energy consumption. Table II shows the main characteristics of each of these approaches. As we can notice all of them are based on distributed algorithms. Most of them require to maintain state information and the neighbors location information for each individual node.

PEAS is the exception that cannot offer strong guarantees about the degree of coverage or connectivity, but

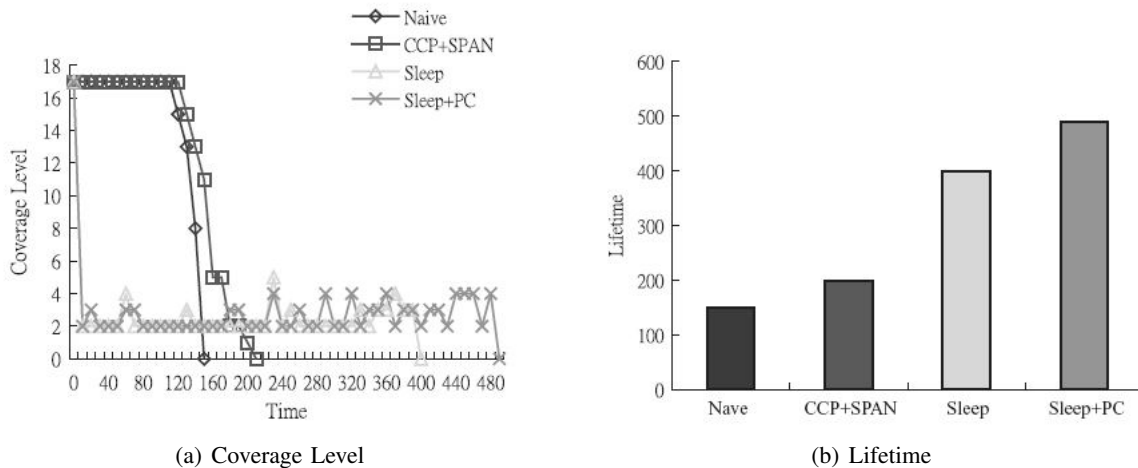


Fig. 6. Comparison between Naive, CCP+SPAN, Sleep and Sleep+PC Protocols [1]

TABLE II
INTEGRATED COVERAGE AND CONNECTIVITY PROTOCOLS

Approach	R_s vs R_c	k_s	k_c	Deployment	Observations
CCP [1]	CCP for $R_c \geq 2R_s$ CCP+SPAN for $R_c < 2R_s$	k	k	Randomized	-Adjustable coverage degree; -Sensor nodes with uniform characteristics -State & location information
PEAS [12]	ANY	NA	NA	Randomized	-Probing range, adaptive sleep -No state/location information
OGDC [9]	$R_c \geq 2R_s$	1	1	Randomized	-Rounds, time sync -Sensor nodes with uniform characteristics -State & location information -Optimality conditions
Otawa [10]	$R_c \geq 2R_s$	k	k	Randomized	-Random sequence -Sensor nodes with uniform characteristics -State & location information
Sleep+PC [11]	ANY	k_s	k_c	Randomized	-Generalized solution -Sensor nodes with different characteristics -State & location information

it provides an interesting solution for applications that require a high degree of adaptivity. PEAS is also a good approach when we want to use a simple lightweight protocol (no state information is maintained, nor neighbor location information is required).

One of the difference between OGDC and CCP is that OGDC uses rounds and thus require time synchronization among nodes, while in CCP each node executes its own state without a global synchronization requirement. Another difference is that OGDC tries to optimize the set of active nodes based on their relative location (optimality conditions) whenever possible.

Sleep+PC is one of the most generic approaches which make no assumptions on the relationship between sensing range and communication range and supports nodes with different characteristics. In addition its performance in maximizing the network lifetime seems to be the best

from all other approaches if we consider their evaluation results.

V. CONCLUSIONS

This paper surveyed several solutions for energy conservation in wireless sensor networks. As we have already seen early work focused only on the coverage problem. The widely adopted solution is to schedule nodes into sleep state whenever possible while ensuring coverage preservation. Most of these works do not consider different coverage degrees and adopt centralized algorithms for the scheduling mechanism. On the other hand, more recent research focus on the integrated coverage and connectivity problem. Some of these use mathematical relationships between the sensing range and communication range and simplify the integrated problem into a traditional coverage problem. The assumptions

are that all sensor nodes have uniform properties (same sensing range / communication range / initial energy etc) and that the communication range is at least twice the sensing range. However these solutions cannot be applied always in real networks. Specifically, whenever these particular assumptions do not hold. In contrast to this trend, [11] provide generic theorems which ensure both coverage and connectivity in more real scenarios where the sensor nodes may have different properties. Moreover, to conserve further energy [11] combines the traditional scheduling mechanism with power management and show an improved efficiency.

In the following I emphasize some lessons learned while studying the integrated coverage and connectivity problem:

- **Connectivity does not imply coverage as nor coverage imply connectivity:** Even it might be confusing at the first time, as these terms are quite related, in the general case there is no certain relationship required between sensing range (coverage) and communication range (connectivity). However, there might be particular situations when the coverage imply connectivity, as already showed in the paper. Notice that the reverse is not always true.
- **Decentralized solutions preferred:** In all the presented solutions for the integrated problem decentralized solutions were employed as these are more appropriate for high density sensor networks. The centralized solutions have the advantages in controlling all the nodes without additional time synchronization or backoff mechanisms required. However, the central node can be a potential bottleneck in high density networks.
- **Backoff mechanisms are a requirement:** Decentralized solutions require backoff mechanisms to protect multiple nodes in taking similar actions (entering in the sleep mode) at the same time.
- **Combining different methods to conserve energy may be a good idea:** This paper surveyed mostly scheduling as a mechanism to conserve power consumption in wireless sensor networks. However, [11] showed that combining scheduling with power management, which limits the transmission power of sensors, may be more effective than using scheduling only.
- **Redundancy can be useful:** Early protocols ensure only 1-coverage. However, a higher degree of coverage may be desirable to ensure the robustness of applications. The more recent protocols can guarantee k-coverage and this should be considered by applications that require a certain level of robustness.
- **Real conditions:** All of the presented solutions used simulation to check the effectiveness of their proposed algorithms. However, I consider that other variables (from the real environments) should be also considered. For instance obstacles can obstruct the sensing ranges of some sensors or noises can interfere with the communication. These parameters may considerably affect the above discussed protocols.

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