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Coverage-Preserving and Energy-Conserving Protocols for Wireless Sensor Networks

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Coverage-Preserving and Energy-Conserving Protocols for Wireless Sensor Networks

by

Xin Fei

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Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the M.Sc. degree in
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Abstract

Keeping sensing coverage while saving energy of wireless sensor network is one of major challenges in wireless sensor network which includes three fundamental research aspects: *coverage discover methods*, *conflict resolve algorithm* and *wakeup strategy*. By means of computing geometry and computer graphics some solutions proposed for the wired sensor network were transplanted to the wireless sensor network. However, the heavy message overhead and the centralized model made most of them can not gracefully handle the more restrict conditions in the wireless sensor network to resolve *Coverage Problem*. In this thesis, we propose efficient coverage-preserving and energy-conserving protocols for wireless sensor networks. We discuss our protocols and their implementation using ns-2 simulator. We also present an extensive set of simulation experiments to evaluate their performance using several scenarios.

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Chapter 1

Introduction

1.1 Wireless Sensor Network

In recent years, Wireless sensor networks (WSN) have been used in many situations, such as habitat monitoring, EOFS (Environment Observation and Forecasting System) applications, health applications, battlefield monitoring, museums security, weather detection, wild animal protection [30] and some other critical areas where are human inaccessible. WSN have to provide a fast, reliable, fault tolerant and energy aware channel to meet the requirements of different sensor network application scenarios, such as query-based (when a sink queries the WSN for specific information), event-driven (sensor nodes send information to the sink upon detecting an event) and periodic (sensor nodes send information to the sink periodically) [1, 3, 10]. The critical environments make the replacement of power be impossible and arise the energy saving issues to the front line of research.

1.2 Problem Statement

1.2.1 General Challenges of WSN

The most challenging research brought by such requirements is: How to keep the net in a good monitoring quality and live as long as possible. Such challenge is often related to the QoS issue and known as Energy Aware Coverage which includes many perspectives such as: How to keep good quality monitoring in face of high rates of failure? What is the optimal number of nodes that meets coverage quality? How guaranteed is the detection (and delivery) of a critical event within a given time frame? What are the breach points in a sensor field? When tracking of people or objects is required, as in a search for survivors during a critical condition, what is the optimal number of nodes necessary for target detection? How accurate is the location? Moreover, for the supervision and control applications, different types of sensors with different processing power and communication properties (radio range) might be integrated with themselves and with actuators (actors - more resourceful nodes with capability to respond to events in real-time) in the same WSN; How can coverage be met with heterogeneous sensors? However, a solution that addresses all the issues raised above, simultaneously, poses great challenges.

We concentrate the research challenges on the software of wireless sensor network in the following aspects:

- **Self Organization & Maintenance:** Dynamic deployment requires that the system copes with the problem of connectivity and dynamic environmental conditions changes: High densely deployed sensors require sensors manage their transmission range and transmission schedule to avoid collisions and congestion;
- **Power Management:** Sensors are very limited in power, computational capacities and memory. Low-cost deployment is one acclaimed advantage of sensor networks. Limited processor bandwidth and small memory are two arguable constraints in

sensor networks, which may disappear with the development of fabrication techniques. However, the energy constraint is unlikely to be solved soon due to slow progress in developing battery capacity. Moreover, the intended nature of sensor nodes and hazardous sensing environments preclude battery replacement as a feasible solution. It requires the protocols are energy-aware, energy-saving.

- **Quality Management:** Keeping sensor network working in a high quality manner is another challenge requirement which include quality evaluation methods and the ways to improve the monitoring quality.
- **Security and Privacy:** In contrast to traditional networks, sensor nodes are often deployed in accessible areas, presenting a risk of physical attacks. Sensor networks interact closely with their physical environment and with people, posing additional security problems. Because of these reasons current security mechanisms are inadequate for WSN. These new constraints pose new research challenges on key establishment, secrecy and authentication, privacy, robustness to denial-of-service attacks, secure routing, and node capture.
- **Real-Time:** In many cases, sensor data must be delivered within time constraints so that appropriate observations can be made or actions taken. Very few results exist to date regarding meeting real-time requirements in WSN. Most protocols either ignore real-time or simply attempt to process as fast as possible and hope that this speed is sufficient to meet deadlines.
- **Real-world Protocols:** Many current WSN solutions are developed with simplifying assumptions about wireless communication and the environment, even though the realities of wireless communication and environmental sensing are well known. Many of these solutions work very well in simulation. It is either unknown how the solutions work in the real world or they can be shown to work poorly in practice.

1.2.2 Challenges in Coverage Problem

Keeping sensing coverage while saving energy of wireless sensor network is one of major challenges in wireless sensor network which involved almost all the requirements presented above. Coverage preserving off-duty scheme is a frequently used energy saving protocol in the wireless sensor network. It includes three research aspects: Coverage Discover Methods, Conflict resolve algorithm and Wakeup Strategy. By means of computing geometry and Computer Graphics some solutions proposed for the wired sensor network were transplanted to the wireless sensor network. However, the heavy message overhead and the centralized model made most of them can not gracefully handle the more restrict conditions in the wireless sensor network to resolve Coverage Problem. A decentralized, light message overhead algorithm was respected.

- Coverage Discover Methods: the key challenge of such scheme is the method of identifying all fully sponsored sensors without error which decided how well off-duty scheme can save energy and keep the monitoring quality of wireless sensing network. Several centralized/decentralized solutions based on the geometry information and under the assumption of disk sensing range have been introduced even the disk assumption is too strong in the real world and can not be hold in a high precision required scenario.
- Conflict-Resolving Algorithms: Beside the coverage discover methods how to resolve the conflict of two eligible candidates is another importance issue of coverage problem. The message overhead and the ability of keeping the initial coverage are all the interesting subjects concerned by algorithms.
- Wakeup Scheme: As an inseparable part of off-duty scheme wakeup strategy is an important issue in the coverage problem. It is mostly concerned as a research on the physical level even it highly effect the performance of protocols on the energy saving issue. Some power management schemes require that each network node wake up periodically while some other schemes require an extra equipment

to listen a wakeup channel. How can we keep the wakeup scheme cost energy as less as possible while did not affect the coverage rate is the goal of such challenge.

1.3 Motivation

Our works presented in this thesis are firstly inspired by the works of Tian and Georganas, which we refer to as C-PNSS[15], in which a node scheduling scheme is based on off-duty eligibility rules, which allows nodes to turn themselves off so long as there are neighbor nodes that can cover the area for them. Base on the work of C-PNSS, we proposed our first part of work in the OCoPS(Optimal Coverage Preserving Scheme). In the OCoPS, an Association Sponsors Method is described in order to enhance the Central Angles Method introduced by C-PNSS and a sensing wakeup strategy was first discussed. To get over the drawback of heavy control messages in the OCoPS, another two decision algorithms: ON-E and Alt-E were developed.

1.4 Contribution

The main contributions of this thesis are:

- 1. A extended center angles methods(Association Sponsors) is proposed base on the cycle sensing range assumption and remarkably improves the network lifetime by increasing off-duty sensors while keeping the coverage.
- 2. To avoid the holes generated by conflicts and save the energy cost on the control messages three election algorithms(OFF-E, ON-E, Alt-E) are developed base on the message synchronization instead of time synchronization.
- 3. A wakeup scheme is firstly discussed detailed while weak points of period wakeup scheme which is frequently used in Off-duty scheme of wireless sensing network

was point out. To overcome withdraw of period wakeup scheme a sensing wakeup scheme based on reasonable assumptions is submitted.

1.5 Thesis Outline

The rest of this thesis is organized as follows:

- Chapter 2 introduces some related work and background knowledge.
- Chapter 3.1 gives some basic definitions used in this thesis.
- Chapter 3 presents OCoPS scheme.
- Chapter 4 presents ON-duty election algorithm and Alternate election algorithms.
- Chapter 5 concludes this thesis.

Chapter 2

Background and Related Works

2.1 Coverage of Wireless Sensor Network

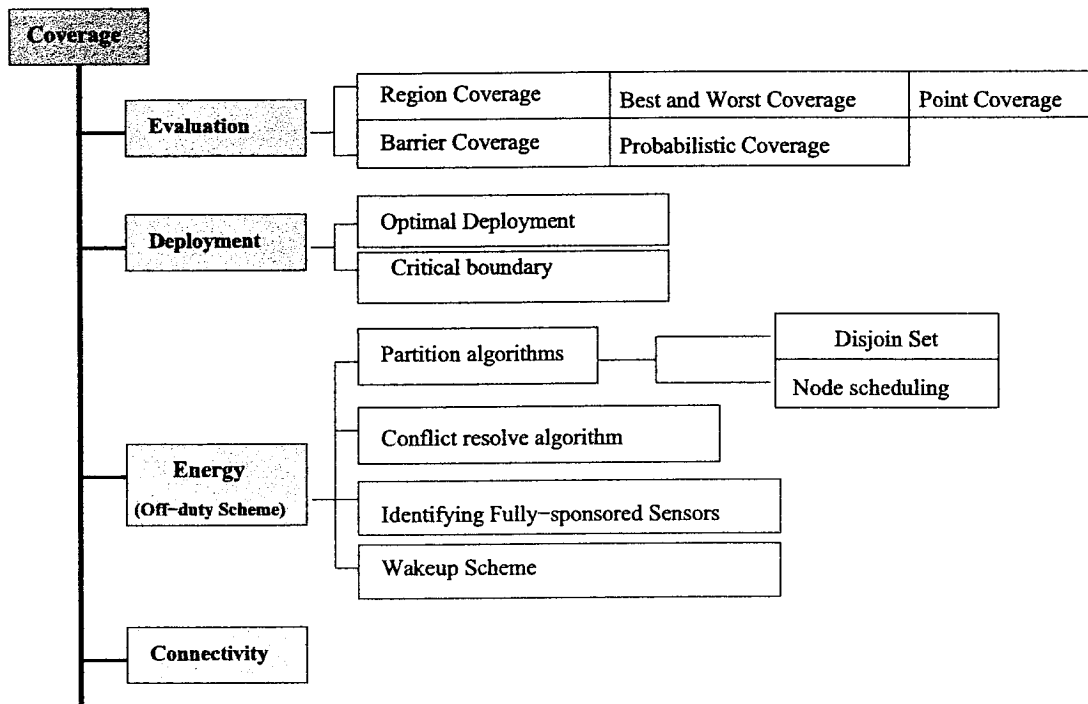


Figure 2.1: Classification of Coverage Problems

Basically, the coverage problems of WSN were defined either as deterministic (static) or nondeterministic (dynamic) deployment [33]. Because most wireless sensors were typically randomly deployed in difficult-to-access environments, nondeterministic deployment catches more attention than deterministic deployment. At the same time, distributed or decentralized solutions, which keeps coverage while keeping network long life, become interesting research topics of non-deterministic deployment. In this chapter We will classify the work of coverage problems as figure2.1 and briefly described some novel works.

2.2 Evaluation Methods of Coverage Problem for Wireless sensor Network

Coverage is firstly considered as a primary factor to evaluate the monitoring quality of wireless sensor network. Based on different quality requirements and scenarios researchers propose several different definitions described in this section.

2.2.1 Region Coverage

The first well defined coverage problem is the region coverage problem, where the main objective is that how well a region can be monitored by a wireless sensor network. Such problem commonly was considered that it was first introduced into wireless sensor network by the art gallery problem (AGP) [42], which is about how to determine the minimum number of guards required to cover the interior of an art gallery (represented by a polygon). The algorithm showed in the AGP can solved such problem optimally in two-dimensional while shown to be NP-hard in the three-dimensional case. Because in the nondeterministic high density wireless sensor network the monitor area are always assumed fully covered by sensors, the research of region coverage problem are always included in some other issues such as coverage quality, network connectivity, energy issues and deployment methods.

2.2.2 Point Coverage

The objective of point coverage problem is to investigate that how well a wireless sensing network covers a set of points. The requirement is that every target must be monitored at all times by at least one sensor(1-coverage). Kar and Banerjee [39] develop an algorithm to deploy a connected sensor network so as to cover a set of points in Euclidean space. This algorithm, which assumes that $R_s(\text{Sensingrange}) = R_t(\text{Transmissionrange})$, uses at most 7.256 times the minimum number of sensors needed to cover the given point set. It is easy to see that the constructed deployment covers all of the given points and is a connected network.

Huang et al.[14] introduces a k -covered problem (where k is a predefined constant) to determine if every point in a given area is sufficiently covered by at least k sensors. To determine which areas are insufficiently covered, [14] assume that there is a central controller in the sensor network, which broadcast a desired value k to all sensors. Each sensor communicates with its neighboring sensors and then determines which segments of its perimeter are less than k -perimeter-covered. The results are sent back to the central controller. By putting all segments together, the central controller can precisely determine which areas are less than k -covered. The irregular sensing range problem was also addressed in [14] and the algorithms were proved that can be applied under both disk sensing range and irregular sensing range. The definition of coverage was extended from 2D to 3D by Huang et al. in[54], in which a polynomial algorithm was proposed for the 3D K -covered problem.

Grid coverage is another version of the point coverage problem. In [41], Chakrabarty et al. present such quest as a two or three-dimensional grid of points where sensor locations are restricted to these grid points and each grid point is to be covered by at least k , $k \geq 1$, sensors. In such problem, the sensors are assumed to have a communication range large enough to reach the base station from any grid position and do not communicate with one another. The objective is to find a least sensor deployment that provides k -coverage. K -coverage with $k > 1$ affords some degree of fault tolerance. Based on

a K -coverage scheme we are able to monitor all points so long as no more than $k - 1$ sensors fail.

2.2.3 Barrier Coverage

Barrier coverage was firstly defined by Gage in in [60] to evaluate multi-robot systems. the objective of Barrier coverage is to minimize the probability of undetected penetration through the barrier. In order to enhance the monitoring quality, Kumar et al.[53] combined the k -covered problem and Barrier Coverage and extended barrier coverage problem to a k -barrier coverage problem where a wireless sensor network is deployed as a belt to guarantee that all crossing paths through the belt are k -covered by the sensor network. Based on probability analysis an efficient algorithm was proposed and several key results were derived, such as the optimal number of sensors needed to achieve k -barrier coverage. Authors pointed out that even full k -coverage can be determined locally[14] it is impossible to locally determine that a given region is k -barrier covered. Equivalence conditions were given between k -barrier coverage and the existence of k node-disjoint paths between two vertices in a graph. Based on such conditions, algorithms already existing to test the existence of k node-disjoint paths can be used to identify a k -barrier covered region.

By study with high probability two notions of barrier coverage, weak and strong barrier coverage, were introduced.

Definition 1 weakly k -barrier covered

A belt region is said to be weakly k -barrier covered with high probability if and only if $\forall i : \limPr[\forall j \in L(i) : j \text{ is } k\text{-covered}] = 1$, where i is a crossing path through a belt region and $L(i)$ is the set of all crossing paths congruent to i .

Definition 2 strongly k -barrier covered

A belt region is said to be strongly k -barrier covered with high probability if and only if $\limPr[\forall i : i \text{ is } k\text{-covered}] = 1$, where i is a crossing path through a belt region.

A optimal deployment pattern to achieve k-barrier coverage is showed by deploying k rows of sensors on the shortest path across the length of the belt region such that consecutive sensor sensing disks abut each other.

2.2.4 Worst and Best Coverage

Worst and best case coverage are used to evaluate the service quality of the WSN. In worst-case coverage, attempts are made to quantify the quality of service by finding areas of lower observability and detecting breach regions. In best-case coverage, finding areas of high observability and identifying the best support and guidance regions are of primary concern.

In [32], authors propose an optimal polynomial time algorithm which combines graph theory and computational geometry (Voronoi constructs) to resolve the best and worse case coverage by investigating the breach paths. Meguerdichian et al. addressed the problem as: given a field instrumented with sensors and the initial and final locations of a mobile agent to determine a maximal breach path (MBP) and the maximal support path (MSP) of such agent. The MBP (MSP) corresponds to the worst (best) case coverage and has a property that, for any point on the path, the distance to the closest sensor is maximized (minimized). The algorithm assumes that sensor nodes are homogeneous and know sensor locations. Based on the observation that MBP lies on the *Voronoi* diagram lines and MSP lies on *Delaunay* triangulation lines, the proposed algorithm starts by generating the Voronoi diagram (or Delaunay triangulation diagram) and assigns every segment a weight equal to the distance to the closest sensor (or equal with the segment length). The path is finally computed by a binary-search or Breadth-First-Search.

Relative neighborhood graph was introduced in [43], where Li et al. proposed a distributed algorithm for MSP computation. The authors consider two extensions, namely MSP with least energy consumption and MSP with smallest path distance. Liu and Towsley [44] address this penetration path detectability problem in the context of random grid-based sensor networks and propose a critical density for a given sensor network

based on percolation theory.

Differently from work in the [32] Meguerdichian et al. introduced another *exposure-based model* in [45] where another important factor (the sensing time-exposure) is mentioned that the longer the exposure time, the greater the sensing ability. A 2D sensing model is defined as $S(s, p) = \frac{\lambda}{[d(s, p)]^k}$ where $d(s, p)$ is the Euclidean distance between the sensor s and the point p , and λ and k are sensor technology dependent parameters. Another characteristic is the intensity of the sensor field. For example, n sensors s_1, s_2, \dots, s_n in the field F , all-sensor field intensity for a point p is $I(F, p) = \sum_1^n S(S_i, p)$. The exposure of an object moving in the sensor field during the interval $[t_1, t_2]$ along the path $p(t)$ is defined as $E(p(t), t_1, t_2) = \int_{t_1}^{t_2} I(F, p(t)) \left| \frac{dp(t)}{dt} \right| dt$. Because the exposure analytical computation is intractable, the solution proposed uses a grid-based approach to transform the problem domain to a tractable discrete domain. The minimal exposure path in each grid square is restricted to line segments connecting any two vertices. And the grid is transformed into a weighted graph, where the weight (exposure) of an edge is approximated using numerical techniques. Finally, the Dijkstra's single-source-shortest-path algorithm is used to find the minimal exposure path between any arbitrary starting and ending points on the grid. The approximation quality improves by increasing the grid divisions, at a cost of higher storage and run-time.

Another aspect of the exposure-based model is pointed out in [46]. To estimate the sensor node deployment density, one should consider both the sensor characteristics as well as target specifications. For example, detection of an enemy tank requires less nodes due to the strong acoustic signal, compared with soldier detection that might require more sensors. Authors assume the target moves in a straight-line path between two given points with a constant speed. Two radii are associated for a given sensor: radius of complete influence defined as the distance from the sensor such that all targets originating within this radius are detected, and radius of no influence with the property that any target originating beyond it cannot be detected. Using the sensing and exposure model described above, and knowing the threshold energy $E_{threshold}$ required detecting a

target, Authors propose a solution to calculate the influence radii as well as the sensor nodes deployment density. Thus, to cover an area A , computing the number of nodes to be deployed as $O(\frac{A}{r^2})$ where r is the radius, achieves a probability of detection of 98% or above.

2.2.5 Probabilistic Coverage

When nondeterministic wireless sensor network was applied in industry more and more, without clearly location information some original analysis methods for coverage of deterministic network became unsatisfied in the nondeterministic wireless sensor network. In order to overcome the problem of gathering location information and reduce the cost of resolving such problem, some probability analysis methods were introduced to evaluate the performance of random deployed wireless sensor network. Such works mostly focus on the Determination of coverage of random deployed wireless sensor network.

A new notation for information coverage was proposed by Wang et al.[59] based on accurate estimation. A point is said to be completed information-covered if there exists enough sensors to keep the estimation error lower than a predefined threshold. A theory and simulation prove were provided to demonstrate that by comparing with original notation of coverage, information coverage can provide an approximate coverage with less density.

2.3 Coverage-Preserving Deployment methods

2.3.1 Optimal Deployment

Optimal deployment is an foundation research area in the static WSN and mostly related to auto deployment or self-deployment in the dynamic WSN. Gage first employed the concept of coverage to evaluate multi-robot systems in [60]. He defines three basic types of coverage: blanket coverage, where the objective is to achieve a static arrangement of

nodes that maximizes the total detection area; barrier coverage, where the objective is to minimize the probability of undetected penetration through the barrier; and sweep coverage, which is more-or-less equivalent to a moving barrier.

In [48], a greedy and incremental self-deployment algorithm for mobile sensors and self deploy is addressed. A collection of mobile sensors are placed into an unknown and potentially hazardous environment. Following the initial placement, the sensors relocate so as to obtain maximum coverage of the unknown environment. They communicate the information they gather to a base station outside of the environment being sensed.

Another distributed potential-field-based algorithm to self deploy mobile sensors under the stated assumptions is developed in [49].

Virtual force algorithm (VFA) was also introduced into deployment problem. For a given number of sensors, VFA attempts to maximize the sensor field coverage using a combination of attractive and repulsive forces according to the distance between each other. During the execution of the force-directed VFA algorithm, sensors do not physically move but a sequence of virtual motion paths is determined for the randomly placed sensors. Once the effective sensor positions are identified, a one-time movement is carried out to redeploy the sensors at these positions.

A virtual-force algorithm to redeploy sensors so as to maximize coverage also is developed by Zou and Chakrabarty [50]. Poduri and Sukhatme [51] develop a distributed self-deployment algorithm that is based on artificial potential fields and which maximizes coverage while ensuring that each sensor has at least k other sensors within its communication range.

2.3.2 Critical Boundary

A computable deployment threshold is highly required for the increasing density. Based on the probability analysis and some reasonable assumptions such as transmission range equal to sensing range, several solutions were discussed.

Gao et al.[55] analyze the redundancy problem in WSN and provide an easy and

relatively accurate estimation on the degree of redundancy without the knowledge of location or directional information. A theoretical analysis shows that under disk sensing range and $R_t(\text{transmission range}) = R_s(\text{Sensing range})$, if a sensor C was fully covered, at least three neighbors and at most five neighbors are needed to cover the sensing area of C. Based on this result the probability of a completely redundant sensor on a random deployment was given as $1 - n0.609^{n-1} \leq Pr\{A\} \leq 1 - n0.609^{n-1} + \varepsilon$ where $\varepsilon = (0.276)^{n-1}n(n-1)/2$. In Boukerche et al.[4], it was proved that such result is not satisfied under $R_t(\text{transmission range}) = 2 * R_s(\text{Sensing range})$ where the low boundary of fully sponsored neighbors can be reduced to two.

To keep a sensing network k-covered, Kumar et al.[56] investigated the boundary value under grid, random and Poisson distribution. A RIS(Random Independent Sleeping) scheme was proposed based on an assigned probability p and it was shown that the network lifetime can be increased by a factor $1/p$. Other works on WSN critical density computation include Adlakha et al.[31] and Ghosh[57] that present a method to deterministically estimate the exact amount of coverage holes under random deployment using Voronoi diagrams. The method uses the static nodes to collaborate and estimate the number of additional mobile nodes needed to be deployed and relocated to optimal positions to maximize coverage.

2.4 Energy-efficient Coverage

In the dynamic wireless sensor network the sensors can not be settled manually. To keep sensing quality the density of network is highly increased and leads to higher communication overhead and energy consumption. A set of power saving aware coverage solutions are developed facing such requirement. Because the random deployment of sensors might lead to redundant nodes that share one same area, in order to extend network lifetime while meeting coverage, a common solution-*Off-Duty scheme*, is to have an optimal number of nodes to be active and to have redundant neighbor nodes to be turned-off. We

will introduce some related protocols in this section.

2.4.1 Methods for Identifying Fully-sponsored Sensors

One of important research areas of off-duty scheme is how to identify the fully sponsored sensor. [14] and [15] present a simple method to determine a fully sponsored node by calculating the center angles of its neighbors. If such center angles can cover the whole 360° (as the gray cycles B, C and D shown in figure 2.2), node A can then be determined as *fully sponsored*. Because the CAM presented in the [15] relies on the $R_t(\text{transmission range}) = 2 * R_s(\text{Sensing range})$ assumption and can not identify all fully sponsored sensors, an extended method is presented in [4], named Association Sponsors Method (ASM). In the ASM method, the assumption was set as the transmission range equals to twice of the sensing range what can remarkably increase the number of off-duty sensors without holes. The Association Sponsors Method considers any neighbors that have overlapped areas and establishes an association relationship between the high overlapped and low overlapped sponsors, as shown in figure 3.2, to increase the off-duty nodes.

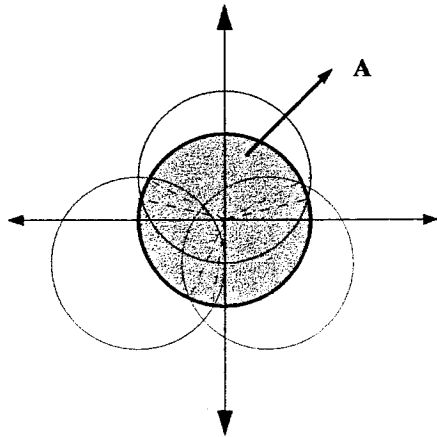


Figure 2.2: Central Angle Method

2.4.2 Partition Algorithms

The main object of off-duty scheme in the dynamic wireless sensor network is to divide the deployed sensors into disjoint sets while every set completely covers all targets. These disjoint sets are activated successively, such that at any moment only one set is active. 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 that 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 probing-based, node-scheduling solution for the energy-efficient coverage problem is proposed in [18] by Ye et al. In such protocol, 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. The protocol works as follows: A sensor broadcasts a probing message PRB within a probing range r_p . Any active node that hears such message will reply with a PRB_RPY message. 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 does not preserve the original coverage area.

In [29], Cardei and Du propose a protocol, which partitions the set of available sensors into disjoint dominating sets such that each set covers all targets in each round. Such dominating sets are modeled in an undirected graph, where sensors form the vertex set and any two neighbors (sensors within each others sensing range) are joined by an edge. Let T be the set of targets to be monitored and let S_i denote the subset of T in the range of sensor i . Let $\{p_1, \dots, p_k\}$ be disjoint partitions of the set of n sensors, if $\cup_{j \in p_i} S_j = T$ the set of sensors in each P_i covers all targets. We refer to the set $\{p_1, \dots, p_k\}$ as a disjoint set whose cover size is k . As shown by the authors 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. Disjoint sets are firstly formed by coloring all nodes, and then applying 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 the algorithm in [34], with lapses in area coverage less than 5%, on average. However, the algorithm of Cardei and Du takes more time to execute and has to fetch the global location information through flooding across the whole network. To avoid the requirement for global information, some interesting works were reported based on node scheduling.

Another energy-efficient node-scheduling-based coverage mechanism is proposed by Tian and Georganas in [15]. The protocol proposed is distributed and localized. The node scheduling scheme is divided into rounds, where each round has a self-scheduling phase followed by a sensing phase. In each self-scheduling phase, the nodes investigate its status by computing its sponsored angles with centre angle methods while a eligibility rule is applying to resolve the conflicts between the candidates. The eligible sensors will be turned off and wakeup until next rounds. To avoid eligible sensors make decision simultaneously which will lead to the blind points, a back-off scheme is used, where every node starts the evaluation rule after a random time, and then broadcasts a status advertisement message (SAM) to announce if it is available for turning off. Before turning off, a node waits another T_w time to listen the SAM from neighboring nodes. The whole work of such scheme is based on that global time synchronization mechanisms is available. It is implemented as an extension of LEACH protocol[36], and simulation results show an increase of 1.7 on average in system lifetime. However, the backup scheme can not

guarantee that all breach holes are avoided.

2.4.3 Wakeup Strategy

As an inseparable part of an off-duty scheme wakeup strategy is an important issue in the coverage problem. It is mostly concerned as a research on the physical level even it highly effect the performance of protocols on the energy saving issue. Some power management schemes require that each network node wake up periodically to listen to the radio channel such as Hui et al.[52]. When an event of interest happens, some nodes detect the event and send power management messages to the network. All the nodes in their listening mode received such power management messages. By choosing a good wake-up/sleep schedule, the network may save much energy without compromising the system functionality. The implementation of the wake-up/sleep scheduling often involves a timer that wakes up the CPU via an interrupt. However, the design of wake-up/sleep schedule is often application dependent and complicated. The time synchronization service is always required.

Another approach is to use a low-power stand-by hardware component such as a radio-transceiver subsystem listening a special radio channel when nodes goes sleep. If the stand-by radio transceiver receives a wakeup radio signals, it wakes the node up. PicoRadio has such functionality [26]. It separates the radio hardware for data communication and channel monitoring. A separate low-power radio, called the *wake-up radio*, monitors the radio channel and wakes up the node when a power management beacon is received. The disadvantage of a stand-by component is that it uses extra energy to keep listen the power management messages.

[28] propose another power management approach, which uses the energy in the event(such as the wakeup message) to trigger the transition of the system from sleep mode to wake-up mode. A special hardware component, radio-triggered circuit, is connected to one of the interrupt inputs of the processor. The circuit itself does not have any power supply. When a power management message is sent by another node (possibly a

sentry node) within a certain distance, the radio-triggered circuit collects enough energy to trigger the interrupt to wake up the network node. So, the node can enter sleep mode without periodic wake-up.

2.5 Connectivity-preserving Coverage

Besides the coverage, connectivity is another important factor for evaluating the quality of WSN. Several solutions have been proposed to guarantee connectivity (Ascent [8], Span [9], Gaf[38]). However, connectivity alone does not guarantee coverage. We often desire that once the sensors are deployed, they organize into a network that must be connected and cover the monitor area as well as possible so that the information collected by sensors can be relayed back to data sinks. An important and frequently addressed issue is to determine a minimal number of working sensors required to maintain the initial coverage area as well as connectivity. So, the power consumption is reduced by less transmission and network lifetime is prolonged. In this section we will present several connected coverage schemes.

Zhang and Hou [19] have established the following necessary and sufficient condition for coverage to imply connectivity.

Theorem 1 *When the sensor density (number of sensors per unit area) is finite, R_t (transmission range) $\geq 2R_s$ (sensing range) is a necessary and sufficient condition for coverage to imply connectivity.*

Another important issue mentioned by [19] 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 nodes 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.

Wang et al. [37] prove a similar result for the case of k -coverage (each point is covered by at least k sensors) and k -connectivity (the communication graph for the deployed sensors is k connected).

Theorem 2 *When R_t (transmission range) $\geq 2R_s$ (sensing range), k -coverage of a convex region implies k -connectivity.*

Based on the theory2, authors proposed a distributed, localized algorithm, called optimal geographical density control (OGDC). In the OGDC 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 changes its state to ON and broadcasts a power-on message which contains location of the sender and a 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. To avoid packet collisions a back-off mechanism was developed.

At the beginning of each round, the status of every node is *UNDECIDED* and will change to ON or OFF state by the power-on messages received. When a node receives a power-on message, it checks whether its sensing area was fully sponsored by its neighbors, and if so, it will change to OFF state. Otherwise, it will change to 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. The simulation experiments based on NS-2 show good results in term of coverage rate and system lifetime.

Base on the theory1, [37] integrate their coverage configuration protocol (CCP) with SPAN [9] to support both coverage and connectivity. SPAN is a well-known distributed algorithm that conserves energy by applying off-duty scheme while maintaining connectivity. The combined eligibility rule is as follows:

- (1) A sleeping node wakeup if it satisfies the eligibility rules of SPAN and CCP;
- (2) An active node go to sleep if it satisfies neither the eligibility rules.

With the eligible rules we can obtain k -coverage through CCP and 1-connectivity through SPAN.

[17] presents another connectivity aware coverage solution in which coverage is achieved through a probing mechanism, which controls the network density. In this algorithm, a node can be in one of three states: sleeping, wake-up and working - when a sleeping node wakes up (after an exponentially distributed period of time), it broadcasts a probing message within a certain range and waits for a reply. If no reply is received within a timeout, it will take over the surveillance task continuously (until it runs out of battery). In this solution, the probing range and wakeup rate can be adjusted to affect the degree of coverage indirectly. However, this solution does not guard against blind points since there is no guarantee on sensing coverage [35].

Because in some cases, the $R_t = R_s$ assumption can efficiently reduced the complexity of algorithms, Carle and Simplot[40] propose another mechanism for energy-efficient connected area coverage. The main idea of such algorithm is to select a connected area-dominating set of nodes of minimum cardinality to covers the given area. [40] rely on other protocols such as tian and Georganas's[15], which we refer to CP-NSS, to decide the status of sensors. When a sensor decided its status a status message was sent to all its neighbors. After that the protocol runs as follows:

- (1) A node p determine whether its monitoring area is fully sponsored by its neighbors;
- (2) After a back-off interval, node p computes a subgraph of its one-hop active neighbors;
- (3) If the subgraph is connected and fully covers p 's area, then node p will be in the sleep mode, otherwise it will be in the active mode during the next round.

Chapter 3

Optimal Coverage Preserving Scheme-OCoPS

In order to avoid waking up more nodes than necessary and keeping connectivity and coverage of the network while optimizing the number of nodes, an optimal coverage-preserving scheme (OCoPS) was devised. This scheme extends the center angle calculation method used in C-PNSS and uses a devised decision algorithm that dispense the use of global clock synchronization by exchanging local information with neighbors. Our scheme is designed under the following assumptions:

- 1) The sensor network density is high enough that only part of it is necessary to monitor a required region R .
- 2) The region R is large enough, as compared to the sensing range of each sensor node, so that the boundary effects can be ignored.
- 3) All sensors have the same sensing range and communication range, which is at least twice that of the sensing range to guarantee the connectivity (only the disk sensor range is considered here).
- 4) All the events that occur under the sensing range of a sensor can be detected

by that sensor.

- 5) Every sensor has a Unique ID and is aware of its own position. No two sensors will sit exactly at the same location.
- 6) Our algorithm works under an ideal network in which there is no message loss in the transmission.
- 7) The routing Protocol already has information on all neighbor locations.

3.1 Basic Definitions of Coverage Scheme

The basic definitions necessary to understand coverage scheme are described below and serve a basis for our works. Some other definitions of our scheme will be introduced in the next section.

- **Definition 3** (*Transmission Neighboring Set*): Consider a set of sensors $\{p_1 \dots p_n\}$ in a finite area δ . If we assume that r is the radio radius of sensor, then the neighboring sensor set TNS_{p_i} of sensor p_i is defined as:

$$TNS_{p_i} = \{n \in \mathbb{N} \mid \text{distance}(p_i, p_j) \leq r, p_i \neq p_j\}$$

- **Definition 4** (*Sensing Neighboring Set*): Consider a set of sensors $\{p_1 \dots p_n\}$ in a finite area δ . If we assume that r is the sensing radius of sensor, then the neighboring sensor set NE_{p_i} of sensor p_i is defined as:

$$NE_{p_i} = \{n \in \mathbb{N} \mid \text{distance}(p_i, p_j) \leq r, p_i \neq p_j\}$$

(In the research context of this chapter, we only refer the neighboring set to sensing neighboring set if we do not declare.)

- **Definition 5** (*Candidate-Fully Sponsored Sensor*): We refer to a node A as a Candidate or fully sponsored by its neighbors if the sensing area, $S(A)$, is fully covered by $S(NE_A)$, where NE_A represents the neighboring set of sensor A , denote as $NE_A \xrightarrow{\text{sp}} A$.

- **Definition 6 (Edge Sensor):** We refer to a node A as an Edge Sensor if A is not a fully sponsored sensor.
- **Definition 7 (Edge Area):** We refer to a monitor area as an Edge Area if and only if such area is covered only by Edge Sensors.
- **Definition 8 (Candidate Area):** We refer to a monitor area as a Candidate Area if and only if such area is covered only by Candidate.

In order to identify the candidate status of a sensor, it has to be checked that if the sensor is fully sponsored by its neighbors. In our paper we will only consider the disk sensing range . [14, 15] give out a simple method to determine a candidate by calculating the center angles of neighbors. If such center angles can cover the whole 360° as the red, blue and green cycles shown in figure 3.1, the node A can then be determined as *fully sponsored*. Details on how to calculate the coverage through angles can be found in [14, 15]. Even though all of the candidates can be identified, not every candidate can

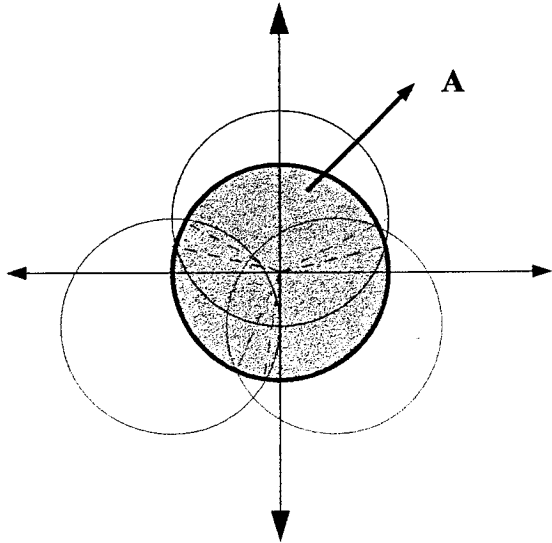


Figure 3.1: Coverage Angle Calculation

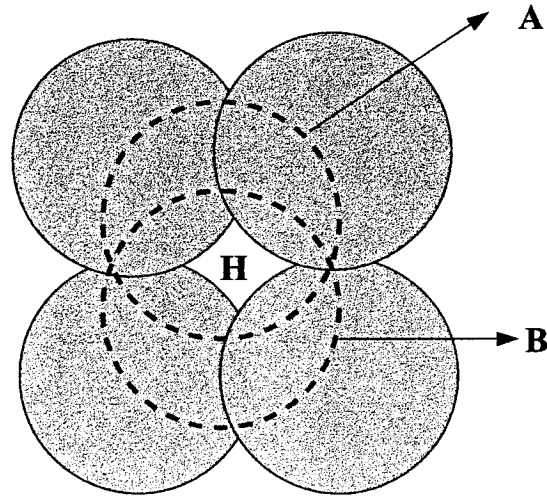


Figure 3.2: Off-duty Conflict

be turned off. For instance, consider the two dash circles in figure 3.2. According to

the definition of *candidate*, the two dash circles ,A and B, are all fully sponsored by their neighbors, but they can not turn themselves off otherwise area H will become a blind point. We call such problem as a *Off-duty Conflict* problem. As mentioned in the previous chapter 2, C-PNSS resolves such problem by a time back-off scheme; however, it can not guarantee that there is no hole is created or not eligible off-duty nodes were set to on-duty.

We then introduce an extended Coverage Angle Calculation method and a *decision algorithm* in the later section that determine the status of candidate nodes and do not rely on a global synchronization clock for the solution.

3.2 Extended Center Angle Method

The method to identify a candidate is a key issue in the coverage problem. C-PNSS [15] proposed a novel method in which the coverage is calculated through the central angles of nodes instead of the coverage area. When combined with the angle antenna, such central angles method can derive a new method for resolving the coverage problem. However, the limitation of this method is that C-PNSS only consider the situation in which the sensing range is equal to the communication range. As pointed in [19], in order to keep the network connected while preserving the coverage, the communication range should be at least double the sensing range. Second, as shown in figure 3.3, the node A, in the center, is fully covered by nodes B, C, D and E but unfortunately such case is ignored by the central angle method mentioned in the C-PNSS because nodes C, D, E will not be considered as neighbors. In other words, because the node A will not be off-duty but rather considered as an edge node, holes can emerge in the intersections among A and C, D or E when C, D, E are out of energy. Thus, the coverage of the whole network will drop earlier and faster. The extended coverage calculation method is explained below, after a required definition.

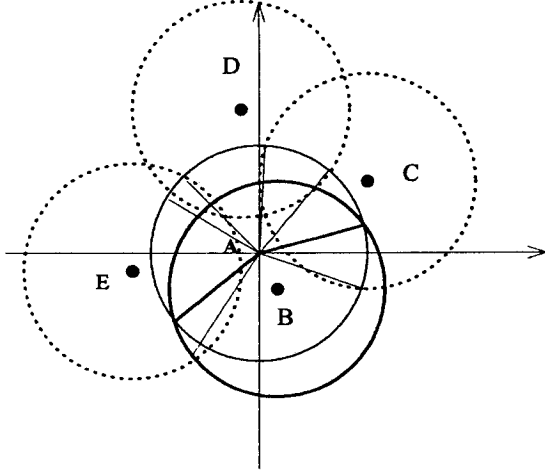


Figure 3.3: Full Coverage when Communication range = 2*Sensing range

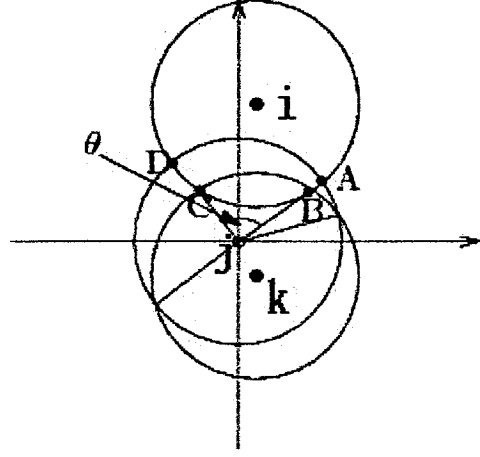


Figure 3.4: Extended Central Angles Calculation

Definition 9 Associated Sponsor

As shown in the figure 3.4, sensor K fully sponsors j with the help of sensor i. In such case, we say sensor K fully sponsors j with i and sensor i is k's associated Sponsor for j, denoted as $K \xrightarrow{sp-i} j$.

As we see in the figure 3.4, when $(2r > d_{i \rightarrow k} > r)$ the sensing area of i, j and K intersect in four points A, B, C, D and create an sponsor area $R_{A \rightarrow B \rightarrow j \rightarrow C \rightarrow D}$. If we extend the line segment $j \rightarrow B$ and $j \rightarrow C$ they will intersect with sensing edge of j in the point B' and C' while we got another area $R_{j \rightarrow B' \rightarrow C'}$ where $R_{j \rightarrow B' \rightarrow C'} \subseteq R_{A \rightarrow B \rightarrow j \rightarrow C \rightarrow D}$ and it can be presented by a fully sponsored angle $\theta_{j \rightarrow B' \rightarrow C'}$. Thus in the case of figure 3.4, the sensor j was fully sponsored by sensor i and sensor k with $\theta_{j \rightarrow i}$ and $\theta_{j \rightarrow B' \rightarrow C'}$.

The $\theta_{j \rightarrow B' \rightarrow C'}$ can be calculated in the following way. For example in the intersect point A of sensor j and k, the coordinates of sensor j and K are known, thus we can get $\alpha_{j \rightarrow k} = \arctan(\frac{Y_k - Y_j}{X_k - X_j})$. As described in the C-PNSS the central angle $\theta_{j \rightarrow k}$ can be calculated by such formula $\theta_{j \rightarrow k} = 2 \cdot \arccos(\frac{d(k,j)}{2 \cdot r})$.

Thus, we can computer the coordinates of A as follows: $X_A = X_j + r \cos(\alpha_{j \rightarrow k} - \theta_{j \rightarrow k})$ and $Y_A = Y_j + r \sin(\alpha_{j \rightarrow k} - \theta_{j \rightarrow k})$ while B, C and D coordinates can be calculated in the

same way. Base on the computations of coordinates of A, B, C, D, we can calculated the fully sponsored angle $\theta_{j \rightarrow B' \rightarrow C'} = \text{actan}(\frac{Y_C - Y_j}{X_C - X_j}) - \text{actan}(\frac{Y_B - Y_j}{X_B - X_j})$.

3.3 The Off-duty Decision Algorithm

To resolve the off-duty conflict problem without using back-off time schedule, a decision process was devised, in which a sensor A can decide its status by exchanging its sponsored angles and contribution angles information with its neighbors. Based on the following definitions the status of a node is decided according to the algorithm3.3:

- **Definition 10** Fixed Sponsored Central Angle

Consider any candidate A and its neighbor B, we say, the overlap angle $FA_{A \rightarrow B}$ is a Fixed Sponsored Central Angle, if and only if B is an On-duty sensor, otherwise we call such angles as Pending Central Angles ,denoted as $PA_{A \rightarrow B}$.

- **Definition 11** Candidate A larger than Candidate B(A > B)

Consider any two candidates, A and B, we say, A larger than B or $A > B$, if and only if $F\Lambda_{A \rightarrow NE_A} > F\Lambda_{B \rightarrow NE_B}$

or $PA_{A \rightarrow NE_A} > PA_{B \rightarrow NE_B}$ while $FA_{A \rightarrow NE_A} = FA_{B \rightarrow NE_B}$

or $ID_A > ID_B$ while $PA_{A \rightarrow NE_A} = PA_{B \rightarrow NE_B}$ and $FA_{A \rightarrow NE_A} = FA_{B \rightarrow NE_B}$

Algorithm 3.3—Decision Algorithm

```
FOR (each candidate node q ) {
  Compare q with all neighbors;
  IF (q is the largest candidate) set q off-duty;
  IF (q is not candidate) set q on-duty;
} //end of loop
```

According to assumption 7 in section 3, the routing Protocol already has information on all neighbor locations. Thus, by counting the messages from neighbors, instead of using time schedule, we can trade the chance of having breaching points in the network

with a bit more control messages. When a candidate receives all status messages from its neighbors, it will start deciding its own status. For that, it will compare its own status with the status of all the neighbors candidate, according to the rules defined above. This node will be off-duty if and only if it is the largest one.

3.4 Wakeup Scheme

3.4.1 Sensing Wakeup Strategy

Several node-scheduling solutions presented in the literature introduce methods to turn off the largest possible number of sensor nodes. However, none of them addresses the wakeup strategy. A wakeup strategy can influence not only the energy consumption in a sensor network but also the quality of the monitoring task. The wakeup strategy is even more important when routing has to be considered. The routing tree can be affected by the wakeup strategy if a dying sensor is part of a routing tree because the waken up sensor has to be taking into the consideration of routing tree construction. Three issues have to be considered in a wakeup strategy:

- 1: *The off-duty sensors should take over the sensing area of dead sensor(sensors that ran out of energy) as soon as possible to avoid coverage holes.*

In the periodical wakeup used in the C-PNSS, if a sensor died between two rounds, events occurring under those sensors can not be detected by any off-duty sensors and the off-duty sensors will only wakeup to monitor the area watched by dead sensor at the beginning of next round. In summary, a hole may appear between two rounds and can not be fixed until off-duty sensors wakeup in the beginning of next round.

- 2: *The wakeup strategy should wakeup off-duty sensors as less as necessary.*

Considering the wake-up process of the two off-duty sensors A and C in the figure 3.5. The following strategy would typically be used: If an on-duty sensor p is

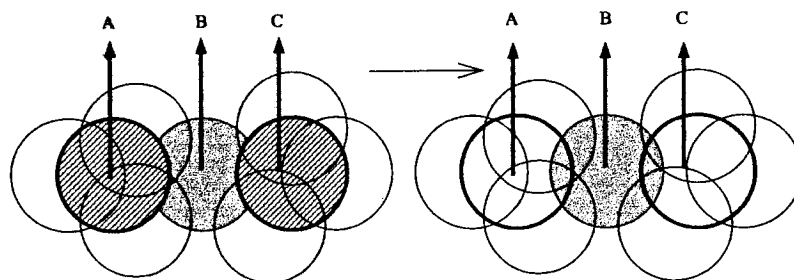


Figure 3.5: Over wakeup

running under low battery, it will broadcast a wake up message to wake up turned-off nodes in its neighbor list. Assuming that on-duty sensor B (the dark circle) is running out of energy and broadcast a wakeup message, then both of off-duty sensors A and C will be wakeup. However, in this case, node A was fully sponsored by its neighbors - in this case we say the off-duty sensor A was *Over-Waken-up*.

- 3: *The wakeup strategy should not be too costly in terms of energy.*

If the wakeup strategy uses much control messages which cost energy even more than what we saved, it is still not as good as our expecting. An alternative solution is to have an additional communication channel(wakeup channel) that receives wake-up messages.

The problem with this solution is that the wakeup channel has to be monitored even when the nodes are off-duty, causing a waste of energy in the the off-duty period. However, it is well known that sensing wastes much less energy than transmitting messages. If a node's energy level can be monitored and its statue of "running out of energy" can be detected as an special event which can be captured by the sensing subsystem of off-duty sensor, a wake-up solution can be devised that avoid the problems with current wake-up strategies and saves energy. This solution works under following *assumptions* and was presented in the algorithm 3.4.1 :

- A1. Dying sensor can generate an out-of-energy event whose energy cost is same as the consumption of transmitting a message;

- A2. Off-duty sensors keep sensing the environment and such action will cost 1.75 Micro Watts consumed for detecting any amount of event (base on the design of *nrlsensorsim*, the energy cost of sensing is around 1/10000 of the transmission energy).
- A3. Assuming the sensing subsystem can detect the distance and angle of event.

Algorithm 3.4.1—Wakeup Strategy

```

For (Each node p that is out of energy)
  Generate an out-off-energy Event;
For
  (each off-duty node q that capture an out-off-energy event
  )
  { identify(event generator);
  recalculate the off-duty status;
  IF(q can not keep the off-duty status){
    wakeup();
    q.status← On-duty;
  }
  }
  
```

3.5 Comparing OCoPS with C-PNSS

Because our optimal coverage calculation method is derived from C-PNSS, we will compare our OCoPS with C-PNSS, first from the principle point of view and then quantitatively in later sections.

C-PNSS is a novel energy aware sensing coverage protocol, which uses less control messages in its initial phase than any other protocol. However, the use of these control messages is repeated round after round-considering the lifetime of the network, not only its initial phase, the energy saving can match other solutions. Moreover, to resolve the *Off-duty* problem a back-off scheme was devised in C-PNSS, which localizes and simplifies

the protocol even it does not guarantee the sensing coverage. In a high density network because of the limitation of Central Angle Method C-PNSS treat some fully sponsored nodes as edge nodes and in the wakeup phase C-PNSS ignore the Association sponsors (mentioned in our scheme), thus it has to wakeup more nodes in order to keep full coverage. On the other hand, considering dying nodes, when network density gets low, C-PNSS can not wakeup enough off-duty nodes to keep the sensing area.

In the OCoPS scheme, it is guaranteed that our algorithm creates no hole and is more efficiently than C-PNSS in the coverage issue. The price for achieving this goal is to use more control messages than C-PNSS in the initial phase (such heavy messages were reduced in the next chapter by new our election algorithms). Moreover, in the OCoPS scheme, off-duty nodes have to be aware of the wakeup event, i.e.. A node has to keep its sensing module working when its other modules (such as transmission/reception) were kept turned off. It is well known that sensing energy consumption is far lower than the message transmission cost. Considering that energy consumption is affected by many factors, such as the size of sensing range, the length of the message, the number of rounds for data gatherings, and the power consumption model itself. In order to compare C-PNSS and OCoPS on the same grounds, we use the same energy parameters and radio model as C-PNSS does, which is showed in table 3.1 and discussed in [36].

Table 3.1: Simulation Parameters

Space	50m*50m
Nodes	50-300
Sensor Range	10m
Package Frequency	0.5s
Initial energy	2J
RTXhresh	$1.9e - 6$
CSThresh	$1.9e - 6$

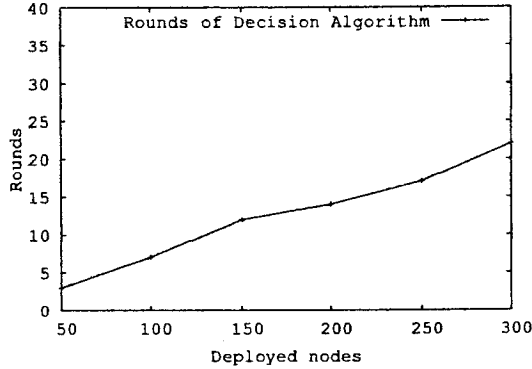


Figure 3.6: Rounds of Decision algorithm

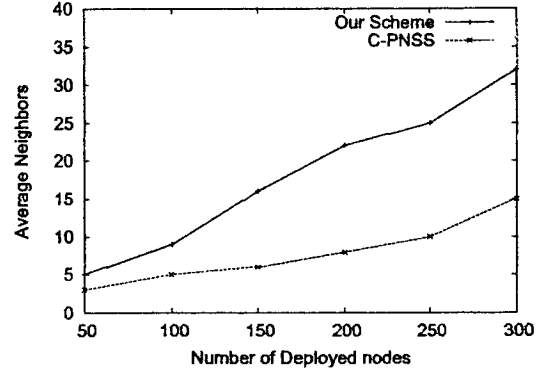


Figure 3.7: Average Neighbors Comparison

What we need to compare with the energy consumption of C-PNSS is the energy cost of our control messages including the energy consumption of catching out-off energy events.

As we know, even C-PNSS use less control messages than other protocols in the initial phase but it has to repeat the same process round by round and in each round the control messages will keep deplete energy. Actually when comparing the extra energy cost among different schemes it should include not only the control messages in the initial phase but also the control messages cause by schemes in the whole lifetime of network. Thus even C-PNSS cost less energy in the initial phase but if we consider the whole lifetime of network it is not better than ours.

Consider a wireless sensor network, which includes N sensors, M candidates, O off-duty sensors and runs T rounds. To simplify the calculation, we assume that the average number of neighbors is X_C in C-PNSS and X_E in OCoPS; the energy cost of sending a message is S ; the energy cost of Receiving a message is R ; the decision algorithm finishes after t rounds and the remaining candidates in the i rounds is M_i . In the wakeup phase, each off-duty node has X_O on-duty neighbors. To guaranty the out-off energy event can be caught, the sensor detect such event 10000 times per round in OCoPS.

In the table 3.2, the lifetime of the network is separated into two phases: initial phase

Table 3.2: Comparison of Energy Cost of Control Messages

Our Scheme			CPNSS		
Initial Phase	PAM	$NS+NX_E R$	Schedule Phase	PAM	$NS+NX_C R$
	SAM	$NS+NX_E R$		SAM	$NS+NX_C R$
	SAM	$\sum_{i=1}^t M_i(S + X_{E_i} R)$			
Run T rounds					
Wakeup Phase	$10000 \cdot T \cdot \text{Sensing}$	$10000 \cdot T \cdot (O_T R / 10000)$	Wakeup Phase	$T \cdot \text{SAM}$	$T \cdot (NS + NX_C R)$
	Event Generating	NS			
	Awake Acknowledge	$N(S + X_O R)$			
Total Cost	$4NS + 2NX_E R + TOR + \sum_{i=1}^t M_i(S + X_{E_i} R)$		Total Cost	$(2+T)(NS+NX_C R)$	
Total Cost	$S(4N + 2NX_E + TO + \sum_{i=1}^t M_i(1 + X_{E_i}))$		Total Cost	$(2+T)(N+NX_C)S$	
Total Cost	$< S(4N + 4NX_C + TN + \sum_{i=1}^t M_i X_C)$		Total Cost	$(2+T)(N+NX_C)S$	
Difference	$D \approx S((\sum_{i=1}^t M_i - (T - 2)N)X_C + 2N) \leq S((t/2 - T + 2)N)X_C + 2N)$				

and wakeup phase. Both schemes will have to exchange messages to gather the location information of neighbors and broadcast status messages to publish its candidate status. Because the information contained in these messages (for gathering and broadcasting status) are almost the same, it is assumed that both types of messages cost the same energy for C-PNSS and for OCoPS. The difference is that, in order to resolve the *Off-duty conflict*, our scheme needs extra messages to publish candidate status, whose energy cost is $\sum_{i=1}^t M_i(S + X_{E_i} R)$. In the initial phase, OCoPS consumes more energy than C-PNSS but not in the long run. Since C-PNSS works in rounds, let us consider the period from end of initial phase to the time that network died after T rounds, referred to as a wakeup phase in the table 3.2.

In OCoPS, because we assume the energy cost of generating an out-of-energy event is same as the cost of sending a message and each sensor only generates one out-off energy event, the total energy cost of generating out-off energy events in our scheme is NS while

the off-duty sensors cost $10000 * T * (OR/10000)$ to catch such events. Because $O \leq N$, we know that $10000 * T * (OR/10000) \leq TNR$. On the other hand, the communication range in OCoPS is double of it in the C-PNSS, to simplify the calculation and base on the experiment data in the figure 3.7, we can assume that $X_E \leq 2X_C$. Knowing that in a fix area $M < N$ but when N is large enough we can ignore the edge nodes or we can say the $M \leq N$. By increasing the number of rounds M_i approach to the $M - O$ which is approach to zero when the M and O are large enough. Thus, we can say that $\sum_{i=1}^t M_i \leq t(N/2)$. It can be seen that t, which presents the average rounds that the decision algorithm have to run, and T, which presents the number of running rounds of C-PNSS, are determinant. t is is increased from 4 to 22 in our simulation result when the number of deployed nodes changes from 50 to 300. T is decided according to the energy of each sensor, as well as the density of the network and the requirement for coverage. Let us consider the situation in which the network density and coverage requirement are the same for both schemes being compared. C-PNSS can perform better than OCoPS when energy is very low but by increasing of energy, the performance of OCoPS surpasses that of C-PNSS. Considering the system setting of table 3.1 with 100 nodes in the 50*50 area, our decision algorithm will stop after 7 rounds and C-PNSS can run at least 10 rounds before sensors start dying. Thus in theory, OCoPS saves more energy on the control messages than C-PNSS does in such scenario. The simulation results, shown in the next section, prove our view.

3.6 Extension of LEACH

In order to compare OCoPS with C-PNSS, OCoPS is implemented and integrated to the LEACH protocol[36] as an extension. This extension includes two phases, initial phase and wakeup phase, which are described below.

3.6.1 Initial Phase

In the initial phase we assume that all neighbors information, which includes location information and ID information, have been collected and prepared by LEACH. Each Sensor starts by calculating the coverage angles and deciding if it is fully sponsored (i.e., if it is covered by its neighbors as show in the figure 3.4), in which case it will be marked as a candidate and its status information will be broadcasted as a CAM message (Candidate Acknowledge Message). Every candidate node, which receives such CAM messages will update its local information and run decision algorithm locally to decide its status until receiving all CAM messages from its neighbors. Decision algorithm will turn off the candidate sensor which is the largest in its neighbor set or set candidate to ON-Duty when it can not keep its fully sponsored status. The status is then broadcast as a SAM (Status Acknowledge Message) message.

When there are sensors running out of energy, an out-off-energy event will be generated. Any off-duty sensor, which detected such wakeup event will update its neighbor list and run the decision algorithm to decide its status again.

The pseudo code for the initial phase is shown below:

Algorithm 3.6.1—Initial Phase

```

Define: CAM Candidate msg
Define: SAM Status msg
FOR(each node p) {
    Computing the center angles by extend methods
    IF (p is a Candidate)
        CAM←(ID,Candidate,SponsorAngles ,ContributedAngles);
    ELSE CAM←(ID,On-duty);
    Broadcast CAM;//Acknowledge neighbors with my candidate status
}

```

```

FOR (each candidate node  $q$  that received acknowledge message) {
  Update Neighbor list;
IF( $q$  received all the CAM from neighbors){
  Run Decision algorithm;
IF ( $q$  is a Candidate)
    SAM←(ID,Candidate,SponsorAngles ,Contributed Angles);
ELSE SAM←(ID, $q$ .Status);
  Broadcast SAM;//Acknowledge neighbors with my status
IF ( $q$  is off-duty) Turn off  $q$ 
  }
} //end of loop

```

3.6.2 Wakeup Phase

Under the assumption we show in the section 3.4.1 (wakeup strategy), when a node p is running out of energy, a wakeup phase starts running. p will generate a wakeup event while an off-duty node q , which captured such event, will identify the generator ID of such event by the distance and angle, and run the decision algorithm. If the node q 's status is not off-duty, it is waken up and a WKM(wakeup message) message is broadcast. The pseudo code for the wake-up phase is shown below.

Algorithm 3.6.2—Wakeup Phase

Define: WKM as the awake message

```

For (Each node p that is out of energy)
  Event(out-off-energy);
For (each off-duty node q that capture an out-off-energy event ){
  identify(event);
  Run Decision Algorithm;
  IF(q is on-duty){
    wakeup();
    WAM = wakeup;
    Broad WAM;
  }
}

```

3.7 Performance Evaluation and Simulation Experiments

3.7.1 Simulation Environment

In order to evaluate the performance of our scheme OCoPS compared to both LEACH and C-PNSS, a set of simulation experiments were carried out using the Network Simulator NS-2 and the setting defined in Table 3.1.

The number of sensors and sink, which were randomly deployed in the $50m \times 50m$ area, varies from 100 to 300. Each sensor has a sensing range of 10 meters and knows the geographical location of its neighbors. For the coverage calculation, the monitoring area was divided into $1m \times 1m$ grids where events were generated every 0.5 second in the cross points.

The simulations goal is to try to prove that OCoPS presents very good performance in preserving coverage and saving energy by testing on the following metrics: Energy

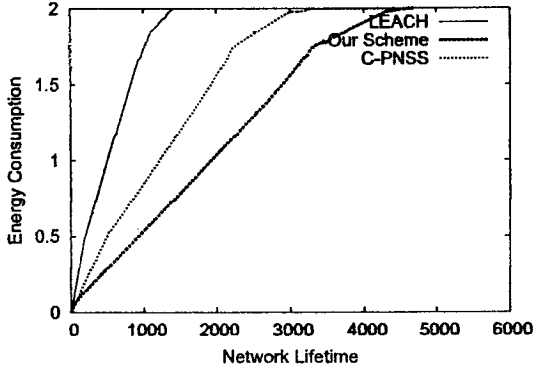


Figure 3.8: Energy dissipation curve per node when $n = 100, r = 10m$

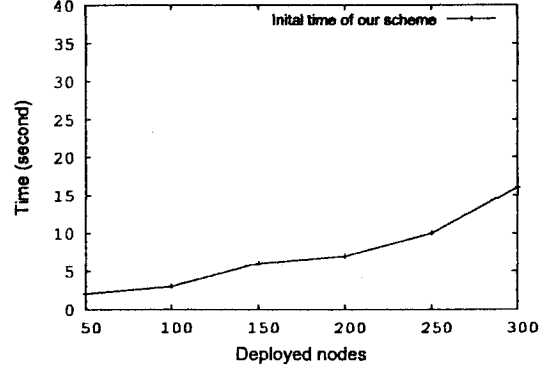


Figure 3.9: Initial Time

Consumption, Network Coverage, Network Lifetime, number of Off-duty nodes and initial phase timing.

3.7.2 Simulation Results

The simulation result for coverage preserving and energy saving are reported below regarding Energy Consumption, Network Coverage, Network Lifetime, number of Off-duty nodes and initial phase timing for LEACH, C-PNSS and OCoPS schemes.

- **Energy Consumption:**

In order to evaluate energy conservation for the three schemes, the following aspects are taken in to consideration: the energy saving in the data-gathering phase, the energy cost of control message used by OCoPS and the energy consumption of sensing and generating the event of "out-off-energy". Figure 3.8 shows that the energy dissipation curve per node in OCoPS is slower than the curves for the other two schemes.

- **Initial Phase Time:**

Figure 3.9 shows the time cost of OCoPS in the initial phase. It can be seen that even when density reaches 300 nodes the initial phase only cost 16 seconds, which when compared with the network lifetime extension provided by our scheme, is very small.

- **Network Coverage**

The purpose of calculating coverage is to evaluate the effect of OCoPS on the monitoring quality when sensors lose energy. The initial coverage is used as the base value (100 percent) and compared with the coverage after applying OCoPS. The goal here is to show that OCoPS does not affect the initial coverage while turning off sensors (Actually when density reach 100 over 50*50 area, the initial coverage can cover the whole 50*50 area). The performance of C-PNSS and OCoPS regarding the shrinking speed of coverage is also shown below.

To calculate sensing coverage, the monitoring space is divided into 1000 $1m \times 1m$ squares where the event sources locate at the cross points. we can roughly calculate the coverage rate by investigating how many events are detected by on-duty nodes. If an event that occurs in the range of the initial sensing coverage cannot be detected by any on-duty node, we call such event source a *blind point*. How well the scheme prevents the occurrence of blind points indicates the coverage preserving ability of scheme.

Figure 3.10 shows that when the number of deployed nodes varies from 50 to 300 there is no blind points appearing in any topology after nodes turned off by OCoPS. This means that OCoPS can really guarantee coverage while turning off sensors.

Figure 3.11 shows coverage along the network lifetime for LEACH, C-PNSS and OCoPS. It can be seen that before sensing coverage drop to 80%, network lifetime under OCoPS was approximately 3240 seconds while under C-PNSS and LEACH was 2330 and 1150 seconds respectively.

- **Network Lifetime:**

Network lifetime is considered here as the time range in which a network has the ability to monitor the environment. One of the purposes of OCoPS is to extend the network lifetime by saving energy. In figure 3.11, when comparing OCoPS with both C-PNSS scheme and LEACH, it can be observed that OCoPS increase the network lifetime nearly 20% more than C-PNSS.

Figure 3.12 shows that with our solution and the CPNSS scheme, system lifetime raises as the node density increases. With the LEACH protocol, the opposite occurs:

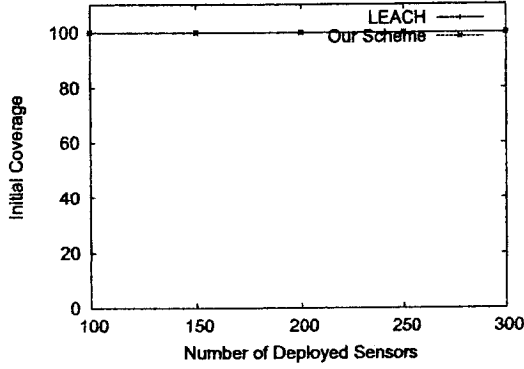


Figure 3.10: Coverage vs. Deployed nodes

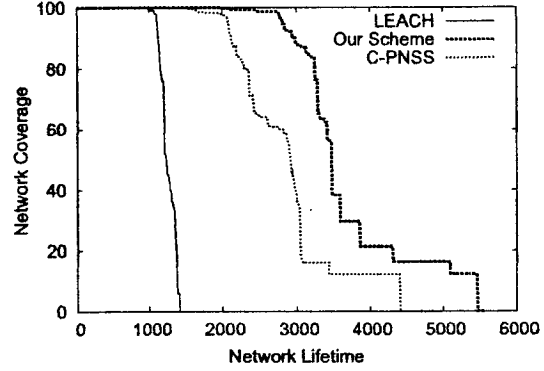


Figure 3.11: Coverage vs. lifetime when $n = 100, r = 10m$

the system lifetime decreases as the node density increases.

• **On-Duty and Off-duty Nodes:**

Figure 3.14 shows the relationship between on-duty nodes and network lifetime for OCoPS compared to the C-PNSS and LEACH. It can be seen, that our algorithm slows down both the speed of nodes death and the waking up of off-duty nodes. Throughout the network lifetime, OCoPS drops slower than the C-PNSS and LEACH. As a result, it takes approximately 5460 seconds for the last node to die, while in the C-PNSS scheme and LEACH, it takes 4410 and 1120 seconds, respectively.

Figure 3.15 shows a comparison among OCoPS, CPNSS and LEACH regarding the relationship between alive nodes and network lifetime. It can be observed that the overhead at the initial stage causes C-PNSS and OCoPS to start losing nodes almost 10 seconds earlier than the original LEACH. It also causes OCoPS to lose the first 5 nodes earlier than the C-PNSS. But after that, the losing rate of OCoPS slows down. Even when the C-PNSS almost runs out of nodes, at around 3000 seconds, our solution still keeps nearly thirty nodes alive.

By applying OCoPS with 100 nodes, 50 nodes can be turned off on average. Under the restriction of coverage higher than 80%, we have varied the network density by varying the deployed node numbers from 50 to 300 in the same $50m \times 50m$ deployed area. Figure

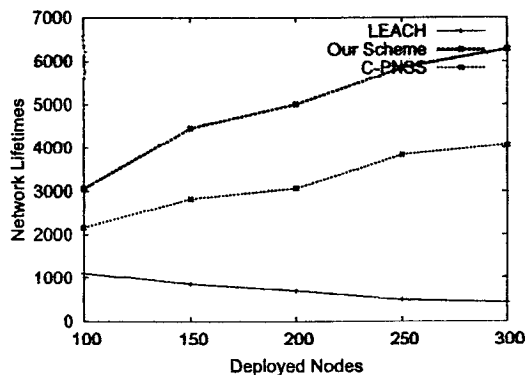


Figure 3.12: lifetime vs. Deployed nodes

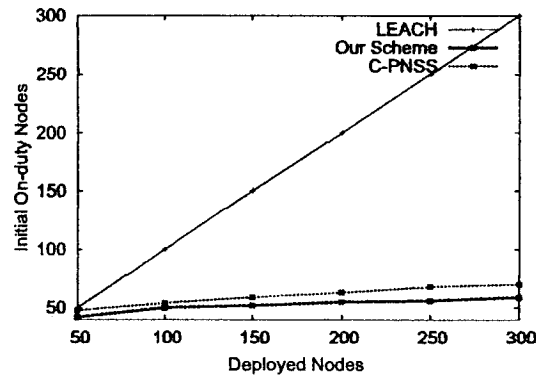


Figure 3.13: Initial On duty nodes vs. deployed nodes

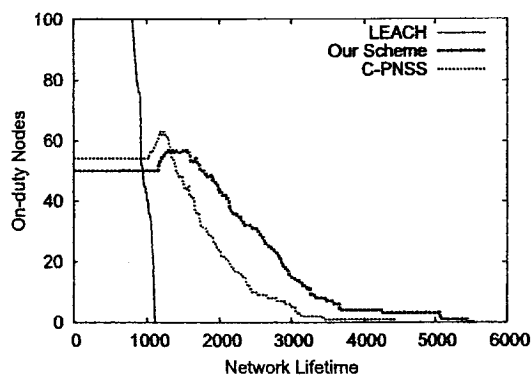


Figure 3.14: On-duty nodes vs. lifetime when $n = 100, r = 10m$

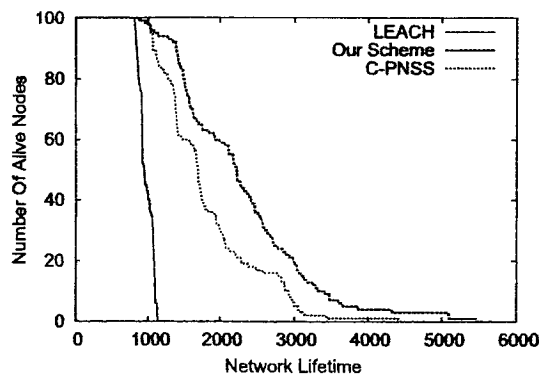


Figure 3.15: Alive nodes vs. lifetime when $n = 100, r = 10m$

3.13 shows that with OCoPS, by increasing the number of deployed nodes, more nodes are turned off. However, the number of on-duty nodes does not remain constant under different deployed node numbers. Rather, it increases as the deployed node number is increased, as illustrated in Figure 3.13. This is due to the random deployment function that does not deploy nodes equally on the area. After the number of total deployed nodes reaches 100 the number of on-duty nodes increases slowly. Simulation result shows that OCoPS effectively limits the on-duty node number. When the deployed node number increases from 100 to 300, the number of on-duty nodes only increased 10%. When

comparing our solution to the C-PNSS scheme, as shown in figure 3.13, we have almost the same number of on-duty nodes as their scheme, even though we use fixed communication range. Figure 3.12 shows that in the on-duty nodes increasing period, that our increasing speed is lower than the C-PNSS, and when the curve enters the dropping period, our dropping speed is lower than C-PNSS. This fact indicates that our wakeup strategy wakes up fewer nodes than the C-PNSS scheme while keeping almost the same coverage rate. Regarding off-duty nodes, the smaller number of messages transmitted in our scheme keeps our off-duty nodes working longer than the off-duty nodes in the C-PNSS, as shown in Table 3.2.

Chapter 4

Conflict-Resolving Algorithms for Coverage-Preserving and Energy-Conserving Protocols for Wireless Sensor Networks

To resolve the *off-duty conflict* problem without using back-off time schedule, a decision process was devised, in which a sensor A can decide its status by exchanging its sponsored angles and contribution angles information with its neighbors. In this decision process three major factors were considered: Number of OFF-duty nodes; Control Message Cost; and Running Time. The first two factors directly affect the energy cost of the whole network, while a short Running time can make the algorithm easier to be inserted into other protocols.

An *Off-Duty Election (Off-E)* algorithm was described and implemented with *Associated Sponsor Method* and *Sensing Wakeup Strategy* in the OCoPS in the chapter 3. OCoPS shows a better performance than C-PNSS which described in the paper [15], however, the heavy control messages of Off-E still keep OCoPS out of exerting all its effort. As the analysis in the section 3.5, the t (running rounds of decision algorithm),

plays a key role in decrease the number of control messages of Off-E. To get over the problem of heavy control message two decision algorithms are developed and described below by reducing the t .

4.1 On-Duty Election Algorithm(On-E)

Reducing the cost of control messages is one of main struggling questions in the decision algorithm. Because the off-duty election algorithm cost too much message and has the potential long running time problem, we are looking for another election algorithm to avoid such problems. The percentage of number of on-duty nodes to the number of deployed nodes attracts our attention. Comparing with Off-duty nodes the On-duty nodes only occupy not more than 20% of total deployed sensors. If we use On-duty election instead of OFF-duty election, it will remarkably reduce the control messages. As we know Coverage Calculation Method can identify the edge nodes and set all edge nodes to On-duty. Thus the duty of decision algorithm is to choose as less on-duty nodes as it can to cover the candidate Area.

Definition 12 Contribution Central Angle

Consider any candidate A and its neighbor set NE_A . We say that the Contribution Central angle $CA_{A \rightarrow NE_A}$ is the summation of $PA_{A \rightarrow NE_A}$ (Pending Central Angles of A as defined in the definition 10).

Definition 13 On-duty Decision Rule:

Consider any two candidates, A and B . We say that A larger than B or $A > B$, if and only if $CA_{A \rightarrow NE_A} > CA_{B \rightarrow NE_B}$ or $PA_{A \rightarrow NE_A} > PA_{B \rightarrow NE_B}$ while $CA_{A \rightarrow NE_A} = CA_{B \rightarrow NE_B}$ or $ID_A > ID_B$ while $PA_{A \rightarrow NE_A} = PA_{B \rightarrow NE_B}$ and $CA_{A \rightarrow NE_A} = CA_{B \rightarrow NE_B}$.

Algorithm 4.1—On-duty Election Algorithm

```

FOR (each candidate node  $q$ ) {
  Compare  $q$  with all its neighbors by On-duty Decision Rule;
  IF ( $q$  is the decision result) set  $q$  on-duty;
  IF ( $q$  is fully sponsored) set  $q$  off-duty;
} //end of loop

```

In the on-duty election algorithm, the sensor with the largest Contribution Angle is elected in its neighborhood. As we know the number of such on-duty nodes is far lower than the number of off-duty nodes, thus the on-duty election algorithm runs faster than the off-duty election algorithm even in the worst case, and on another hand, the control messages is remarkably reduced. On-duty election algorithm reduce the control messages by reducing the rounds of algorithms but it cause another problem that On-duty election turn off less sensors than the off-duty election algorithm because the algorithm start from the unstable status which may cause the more on-duty nodes in resolving *Off-duty conflict* problem. Thus, another alternate election algorithm is developed to keep both rounds t and number of on-duty nodes in a low level, which is described in the next section.

4.2 Alternate Election Algorithm(Alt-E)

Even the On-duty Election algorithm show a better performance on the average than the off-duty algorithm there are still too much control messages wasted in the worst case in which each round only one candidate can be turned off while the control messages received and sent by other nodes are all useless. Another drawback of On-duty is the *Crack Effect* in which the central nodes will have high probability to be elected as the on-duty nodes and the Candidate Area will generate a lot of some pieces of hole between on-duty nodes and off-duty nodes which will cause more on-duty nodes than Off-duty algorithm do.

To resolve such problems an *Alternate Election* algorithm was proposed, in which

only the candidates received stable status announcement messages will involve in the election. The algorithm is separated to *odd* and *even* rounds and starts with the SAM (Status Acknowledge Message) from the On-duty nodes (Edge nodes) after identifying all the candidates and On-duty nodes in the initial phase. Two new statuses, *On-duty Candidate*, *Off-duty Candidate* are introduced as temporary status. In the odd round only the Off-duty election will be performed. Any candidate A that receives a SAM will check the distance between itself and sender. If this distance is smaller than the sensor range r , its status is set to *Off-duty Candidate*, otherwise it is set to *On-duty Candidate*. Such candidate A will classify its neighbors into 4 groups:

- **On-duty neighbors:** Neighbors which sent an On-duty SAM message;
- **Off-duty neighbors:** Neighbors which sent an Off-duty SAM message;
- **Pending Off-duty (P-Off) neighbors:** neighbors whose distance with anyone of On-duty neighbor is lower than r ;
- **Pending ON-duty (P-On) neighbors:** neighbors whose distance with all On-duty neighbors is larger than r ;

In the Even round, any candidate that receives a SAM will update its status to *P-On* and execute the *Extended Coverage Calculation Method*, which is described in the chapter 3 to find out if such candidate is a qualified On-duty node. Status Update rule: the status only update by the high level SAM message. An Odd round will be triggered when a *P-Off* node A received either a SAM message from all of *P-On* neighbors or SAM messages from all neighbors in the zero level. If A is the node selected by the election algorithm, it will be set to *Off-duty*, otherwise it will be set as *P-On*. An even round will be triggered when a *P-On* candidate A receives a SAM message from all of its *Off-duty* candidate neighbors. The center angles of A are recalculated with the new status information gathered from its *P-Off* neighbors. If A can not keep its candidate status, it will be set as *On-duty*, otherwise it will be set as *P-Off*. Algorithm is shown in the below.

Algorithm 4.2 - Alternate Election Algorithm

```

FOR (P-On candidate q in even round) {
  Extended Coverage Calculation;
  IF (q is not candidate) set q on-duty;
} //end of loop

```

```

FOR (P-Off candidate q in odd round) {
  Extended Coverage Calculation;
  Off-duty Election;
} //end of loop

```

4.3 Comparison Among Election Schemes

As show in the table 3.2, the rounds of algorithm t in the initial phase decided the message cost of algorithm. To reduce the messages and initial time we developed another two algorithm ON-E(on-duty election algorithm) and Alt-E(alternate election algoirthm) which we compared in the following table.

Table 4.1: Comparison of Control Messages

	Off-E	On-E	Alt-E
t	4-22	4-6	2-4
M_i	High	Middle	Low
X_{E_i}	High	High	Low

The *Alt-E* algorithm only take 2 more rounds when the numbers of deployed sensors increased from 50 to 300 while t_{Off-E} increased from 4 to 22 and t_{On-E} increased from 4 to 6. The reason of such increasing was owed to that the edge nodes expend to the

boundary of monitoring area when the deployment density keeps increasing in a size-fixed area. On the other hand, because the monitor area is divided into zones from edge nodes to the center by the classify rules of *Alt-E* and in each round only the sensors in the zone will be involved, the M_i and X_{E_i} of *Alt-E* were kept in a low value and the t is mostly effected by the size of monitor area and sensor range r instead of the density, even the edge expanding still effect the running time in some way.

4.4 Extension of LEACH

Both *On-E* and *Alt-E* are implemented in the NS-2. Because the *Alt-E* is based on a different strategy and uses more statuses, initial phase of *Alt-E*s partly different with the initial phase of *Off-E* and *On-E*. We will only give the pseudo code of initial phase of *Alt-E*.

Algorithm 4.4—Initial Phase of Alt-E**Define:** SAM Status msg**FOR**(each p identified its status in the initial round) { $Round \leftarrow 0$; $SAM \leftarrow (ID, Round, Status)$;

Broadcast SAM;

} //end loop

FOR (each candidate p receives SAM) { **IF**($Round \leq Round_{SAM}$){ $Round \leftarrow Round_{SAM} + 1$; **IF** (SAM is On-duty) { **IF** (distance(sender) $>r$) Status $<$ P-ON **ELSE** Status $\leftarrow P - Off$;

}

IF (SAM is Off-duty) Status $\leftarrow P - ON$;

} //end if

Update Neighbor list;

IF((P-off and received all the SAM from P-ON neighbors) **OR** (P-ON and received all the SAM from neighbors)) {

Run Alt-E algorithm;

 $SAM \leftarrow (ID, Round, Status)$;

Broadcast SAM;

}

} //end of loop

4.5 Simulation Experiments

Using the same simulation parameters as described in the table 3.1, we compare the performance of Alt-E, Off-E and On-E on the initial time, initial on-duty nodes, coverage and alive nodes. The results of Alt-E rank the best in the average. And we use the Alt-E algorithm instead of off-E algorithm in the OCoPS and compare the simulation result of OCoPS with C-PNSS again and show the result in the below.

4.5.1 Comparison among Different Decision Algorithms

On-E and Alt-E are designed to resolve the question of control message and initial time. Figure 4.1 shows that comparing with Off-E both of On-E and Alt-E have a shorter initial time while it is not increasing fast by the density. The On-E algorithm trades short initial time with a little bit higher on-duty number as show in the figure 4.2. The reason is that the election algorithm runs independently on all the candidates. Thus the candidates located in the centre of monitor area will have higher priority to be set as on-duty node than the nodes that close to the edge and cause the Candidate area was cracked into several small pieces. Under such scenario the on-duty algorithm will have a little bit more on-duty nodes than off-duty algorithm. When the monitor area is large enough, such crack effect can be ignored while the energy saved from reduced control message will make On-duty election a better performance than the Off-duty election as show in the figure 4.3 and figure 4.4. Alt-E only let part of candidate involved in the algorithm in each round by using probability to separate the monitor area into r wide zone which makes Alt-E show best performance in all three algorithms. Figure 4.3 and figure 4.4 show that by using a better election algorithm the high coverage period ($coverage > 80\%$) is extended and the time of losing first nodes was postponed even the time of whole network is not extended remarkably.

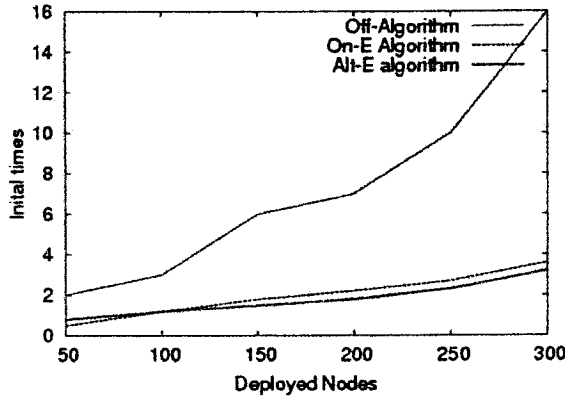


Figure 4.1: Time cost in the initial phase

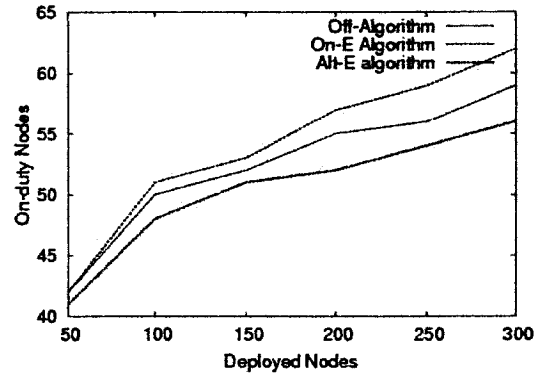


Figure 4.2: Initial on-duty nodes Vs. Deployed nodes

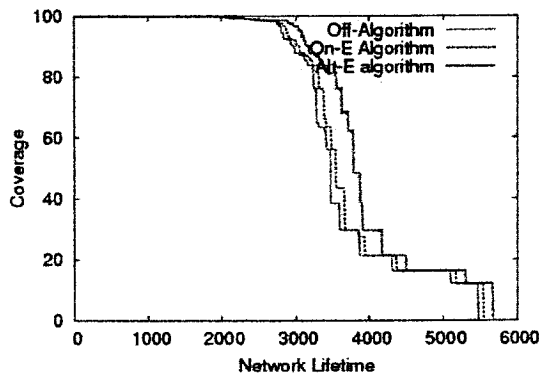


Figure 4.3: Coverage Vs. Lifetime

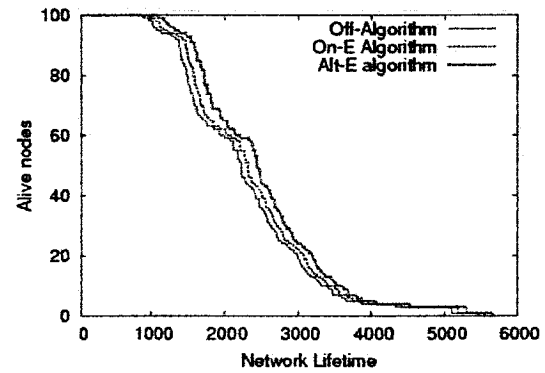


Figure 4.4: Alive nodes Vs. Lifetime

4.5.2 Performance Comparison between Updated OCoPS and C-PNSS

The simulation results for coverage preserving and energy saving are reported below regarding Energy Consumption, Network Coverage, Network Lifetime, number of Off-duty nodes and initial phase timing for C-PNSS and OCoPS schemes.

- **Energy Consumption:**

In order to evaluate energy conservation for the two schemes, the following aspects were taken into consideration: the energy saving in the data-gathering phase, the

energy cost of control messages used by our scheme and the energy consumption of sensing and generating the event *out-of-energy*. Figure 6 shows that the energy dissipation curve per node in our scheme is slower than the curves for the C-PNSS scheme. At 2000 second, the average energy cost of OCoPS reaches 30 % energy saving when compare to C-PNSS scheme.

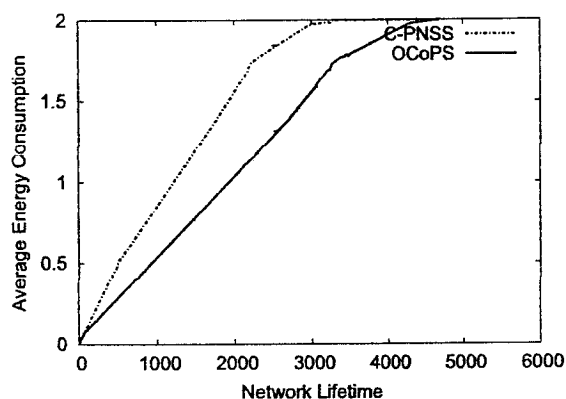


Figure 4.5: Average Energy Dissipation

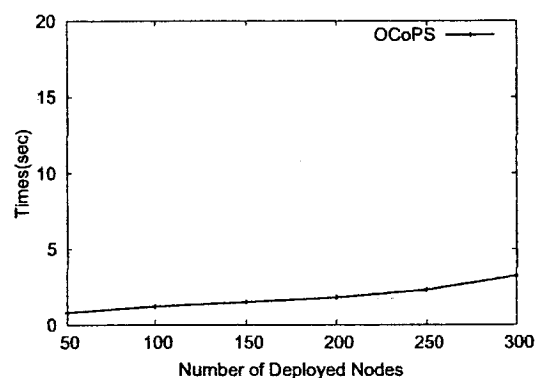


Figure 4.6: Time Cost in the Initial Phase

- **Initial Phase Time:**

Fig. 7 shows the time cost of our scheme in the initial phase. It can be seen that even when density reaches 300 nodes, the initial phase only costs 3.2 seconds, which when compared with the network lifetime extension, 5660 seconds, provided by our scheme, is very small.

- **Network Coverage:**

The purpose of calculating coverage is to evaluate the effect of our scheme OCoPS on the monitoring quality when sensors lose energy. The initial coverage is used as the base value (100 percent) and compared with the coverage after applying our scheme. The goal here is to show that our scheme does not affect the initial coverage while turning off sensors. Actually, when density reaches 100 in a 50*50 area, the initial coverage can cover all of this area. The performance of C-PNSS and our scheme regarding the shrinking speed of coverage is also shown below.

To calculate sensing coverage, the monitoring space is divided into 1000 1m*1m squares where the event sources are located at the cross points. We can roughly calculate the coverage rate by investigating how many events the on-duty nodes detect. If an event that occurs in the range of the initial sensing coverage cannot be detected by any on-duty node, we call such event source a blind point. How well the scheme prevents the occurrence of blind points indicates the coverage preserving ability of the scheme.

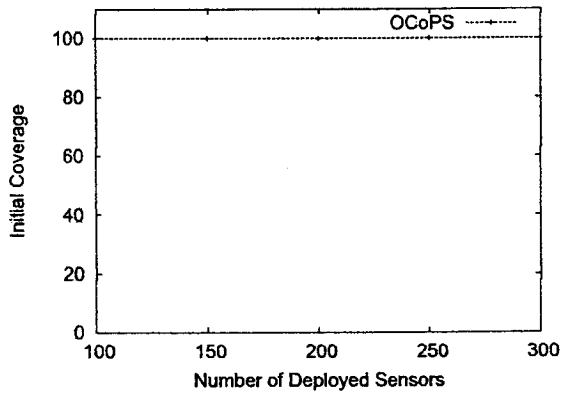


Figure 4.7: Coverage vs Deployed Nodes

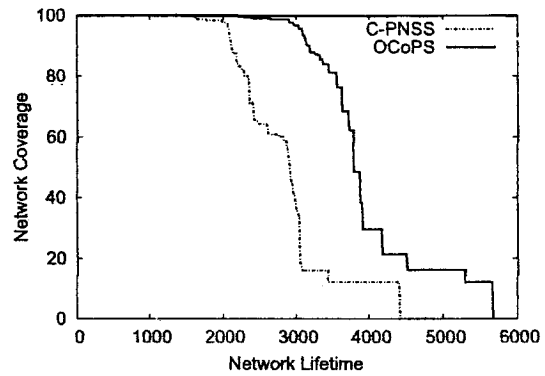


Figure 4.8: Coverage vs LifeTime

Figure 8 shows that when the number of deployed nodes varies from 50 to 300 there are no blind points appearing in any topology after nodes are turned off by our scheme. This means that our scheme can really guarantee coverage while turning off sensors.

Figure 9 shows coverage along the network lifetime for the two schemes. It can be seen that before sensing coverage drops to 80%, network lifetime under our scheme was approximately 3550 seconds while under C-PNSS was 2330 seconds. Thereby our scheme extends the longevity of the network with high area coverage quality.

- **Network Lifetime:**

Network lifetime is considered here as the time range in which a network has the

ability to monitor the environment. One of the purposes of our scheme is to extend the network lifetime by saving energy. In figure 9, when comparing our solution with C-PNSS, it can be observed that our scheme increases the network lifetime nearly 20% more than C-PNSS. Figure 10 shows that with our solution and the C-PNSS scheme, system lifetime increases as the node density increases.

- **On-Duty and Off-duty Nodes:**

Figure 12 shows the relationship between on-duty nodes and network lifetime for the two schemes. It can be seen that our algorithm slows down both the speed of nodes death and the waking up of off-duty nodes. Throughout the network lifetime, our protocol drops slower than the C-PNSS scheme. As a result, it takes approximately 5660 seconds for the last node to die, while in the C-PNSS scheme, it takes 4410 seconds.

Figure 13 shows a comparison among the two solutions regarding the relationship between alive nodes and network lifetime. It can be observed that the overhead at the initial stage causes our scheme to lose the first 5 nodes earlier than the C-PNSS extension. But after that, the losing rate of our scheme slows down. Even when the C-PNSS extension almost runs out of nodes, at around 3000 seconds, our solution still keeps nearly thirty nodes alive.

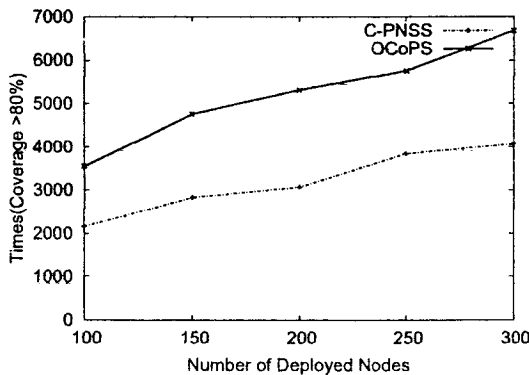


Figure 4.9: LifeTime vs Deployed Nodes

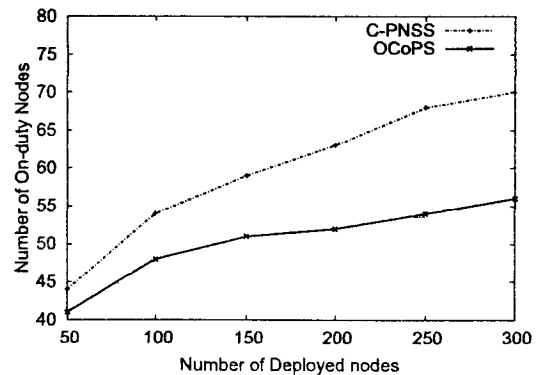


Figure 4.10: On-duty vs Deployed Nodes

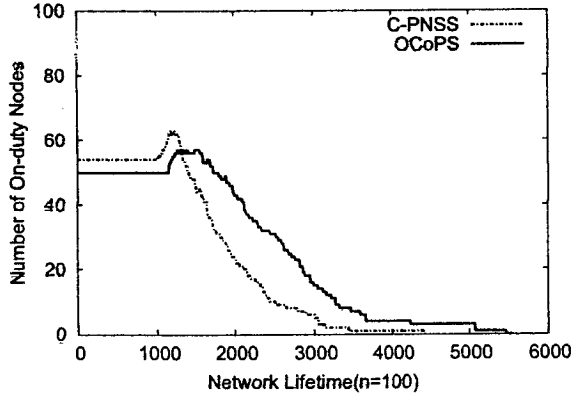


Figure 4.11: On-duty Nodes vs LifeTime

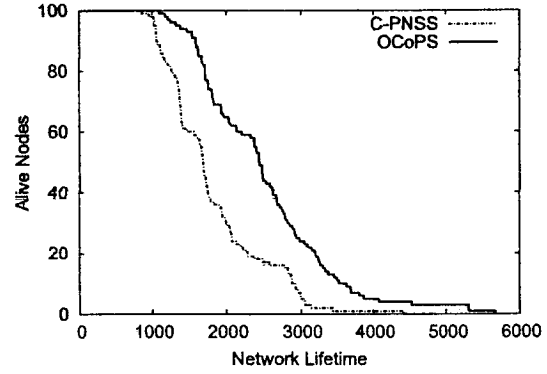


Figure 4.12: Alive Nodes vs LifeTime

By applying our optimal coverage scheme with 100 nodes, 50 nodes can be turned off on average. Under the restriction of coverage higher than 80%, we have varied the network density by varying the deployed node numbers from 50 to 250 in the same 50m*50m deployed area. Figure 11 shows that with our protocol, by increasing the number of deployed nodes, more nodes are turned off. However, the number of on-duty nodes does not remain constant under different deployed node numbers. Rather, it increases as the deployed node number is increased, as illustrated in Figure 11. This is due to the random deployment function that does not deploy nodes equally on the area. The number of on-duty nodes increases slowly after the number of total deployed nodes reaches 100. Simulation results show that our coverage effectively limits the on-duty node number. When the deployed node number increases from 100 to 250, the number of on-duty nodes increased only 10%. When comparing our solution to the C-PNSS scheme, as shown in figure 11, we have almost the same number of on-duty nodes as their scheme, even though we use fixed communication range. Figure 10 shows that in the on-duty nodes increasing period, our increasing speed is lower than that of the C-PNSS scheme, and when the curve enters the dropping period, our dropping speed is lower than the C-PNSS scheme. This fact indicates that our wakeup strategy wakes up fewer nodes than the C-PNSS scheme while keeping almost the same coverage rate.

Regarding on-duty nodes, the smaller number of messages transmitted in our scheme keeps our on-duty nodes working longer than the on-duty nodes in the C-PNSS scheme.

Chapter 5

Conclusion and Further Work

As a challenging topic, coverage problem of wireless sensor network has been discussed in the literature, but most of them focus on the data transmission protocols and base on the static wireless sensor network. In this thesis we systemly analyze the coverage problem and give solutions from the Coverage Discovery Method to the Decision Algorithm and Wakeup Strategy. In this chapter, we will summarize our contributions to the coverage problems of wireless sensor network and outline possible directions for future research.

5.1 Summary of Contributions

In this thesis we focused on the coverage problem of wireless sensor network. First, we classify the works on the coverage problem based upon their characteristics. Then, we presented our contributions and reported the performance of our algorithms using an extensive set of simulation experiments. The contributions of this thesis are as follow:

- We propose a classification of protocols to solve the coverage problem based upon their solutions.
- *Optimal Coverage Preserving Scheme:*
We have proposed a optimal energy aware coverage-preserving scheme for wireless

sensors network, which can resolve the off-duty conflict and guarantee the network coverage by exchanging local information instead of using global information and time scheduling. An Extended Coverage Calculation Method was presented. A simple and efficient decision algorithm was devised as part of our scheme to resolve the Off-duty conflict Problem. A sensing wakeup strategy was firstly addressed. Our experimental results have shown that our scheme exhibits a better performance when compared to both C-PNSS and LEACH where the network was kept running under a high coverage rate without sacrificing the coverage degree.

- *Decision Algorithms for Coverage-Preserving and Energy-Saving Protocols:*
We compared the energy cost of message synchronization and time synchronization and point out that how fast the algorithm of resolving the *off-duty conflict* and how many rounds the node schedule scheme runs are the key points to determine which scheme is better than the other. Three decision algorithms, off-duty Election algorithm, on-duty election algorithm and alternate election algorithm were proposed and compared in the message cost and running time issues. The simulation result shows that The alternate election algorithm has the best performance.

5.2 Further Work

The interest of our further work:

- *Coverage under irregular polygon sensing range :* We will extend our primary works in the coverage problem of wireless sensor network with irregular polygon sensing range, which is presented.
- *Fail-Tolerant Coverage:* We will perform a further study on the fail-tolerant of coverage schemes on the wireless sensor network and aim on improve the service quality of dynamic wireless sensor network

Appendix A

Glossary of Terms

AGP Art Gallery Problem

ALT-E Alternative Election algorithm

ASM Association Sponsor Method

CAM Central Angle Method

CCP Coverage Configuration Protocol

C-PNSS The mode for processing ordinary text.

OCoPS Optimal Coverage-Preserving Scheme

OFF-E Off-duty election algorithm

OGDC Optimal Geographical Density Control

ON-E On-duty election algorithm

MBP Maximal Breach Path

MSP Maximal Support Path

OFF-duty The status of sensors which turned of itself.

ON-duty The status of sensors which keep working.

P-ON Pending On-duty

P-OFF Pending Off-duty

SAM Status Acknowledge Message

VFA Virtual Force Algorithm

WSN Wireless Sensor Network

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