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Le Recouvrement Adaptatif Dans Les Réseaux de Capteurs Sans Fil.

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THESIS

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DOCTORAL DEGREE

In : COMPUTER SCIENCE
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by

Par: Manel CHENAIT

Subject

Adaptive Recovery in Wireless Sensor Networks

Publicly defended on 03/12/2019, in front of the Jury:

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Résumé

Un réseau de capteurs sans fil (RCSF) est un réseau composé d'un grand nombre de capteurs déployés d'une manière aléatoire ou déterministe. Les capteurs sont capables de détecter des phénomnes, traiter des données et communiquer entre eux. La conservation de l'énergie du capteur est un défit majeur dans un RCSF puisque il est difficile de recharger ou de remplacer leurs batteries, en particulier dans les endroits hostiles. Les applications des RCSFs sont multiples, mais la surveillance ou plus généralement la *couverture* est d'une zone d'interet est l'application la plus répondue dans ces réseaux. En effet, la couverture d'une zone d'intért informe est par définition la capacité des capteurs de couvrir chaque point de la zone. Pour augmenter la durée de vie du réseau tout en assurant la k-couverture, l'activation simultanée d'un grand nombre de capteurs s'avére nécessaire. Néanmoins, elle engendre une redondance en l'usage des capteurs.

Pour surmonter cet inconvénient, la plupart des protocoles de couverture emploient, conjointement, deux algorithmes: l'algorithme de détermination de redondance et l'algorithme d'ordonnoncament. Le premier détecte les capteurs redondants et le second planifie leurs activités. Cependant, le passage entre les états, dans la plupart des algorithmes d'ordonnancement, est trés fréquent et dynamique. En effet, un capteur peut inutilement effectuer une séquence de passages entre plusieuers états, pour découvrir qu'il devrait simplement rester dans son état initial. Des énergies de commutation et de calcul supplémentaires sont alors inutilement perdus. En outre, la plupart des algorithmes de determination de redondance sont coteux en terme de temps dexécution.

Dans cette thése, nous proposons deux algorithmes, un d'ordonnoncement, nomme SPEC (Stable and Predictive Energy-efficient Coverage Scheduling) et l'autre de detremination de redondance, nommé SRA (Sector Redundancy Algorithm). Les deux algorithmes cooprent afin daméliorer la qualité de couverture tout en réduisant la consommation inutile dénergie.

SPEC élimine les transitions inutiles entre les états d'activité et de sommeil, il élimine aussi les tests supplémentaires de détermination de redondance.

SRA détermine les nœuds redondants avec le moindre cout possible. En effet, nous avons prouvé qu'un capteur est redondant si un nombre suffisant de ses voisins appartiennent á des sous-régions, bien déterminées, dans son disque de captage. La généralisation de SRA, notée (SRA-Rot), est également décrite dans cette thése. Enfin, le protocole entier de k-couverture, composé de l'algorithme d'ordonnancement SPEC et de l'algorithme de redondance SRA, est aussi décrit et evalué dans cette thése.

Abstract

A wireless sensor network (WSN) is composed of many sensors, that can sense phenomena, process data and communicate with each others. Coverage is an important application in WSNs. It expresses how well a sensing field is monitored by sensors.

To increase the network lifetime while achieving the coverage in WSNs, applications require the simultaneous activation of a large randomly deployed sensors. This situation may incur redundancy as some regions may be monitored by more than the needed sensors. To overcome this drawback, most energy-efficient coverage protocols (EACPs) employ, jointly, two algorithms: a *Coverage Redundancy Algorithm (CRA)* and a *Scheduling Algorithm*. The former determines redundant sensors, while the latter is subsequently run to either eliminate them or plan their activity (active or sleep). However, the switch between states, in most scheduling algorithms, is very frequent and dynamic. Therefore, a sensor may uselessly perform a sequence of switches to finally discover that it should simply remain in its initial state. An extra switch and computation energies are then recorded due to useless transitions and repeated CRA. Moreover, most CRA algorithms are costly, as they have a high complexity running time. This causes not only further computation energy waste but may delay the redundancy detection as well. In this thesis, we first suggest a new taxonomy of EACPs in WSNs, then we propose two new algorithms: SPEC (Stable and Predictive Energy-efficient Coverage Scheduling), which is a new scheduling algorithm and SRA (Sector Redundancy Algorithm), a new CRA. SPEC maintains the coverage quality and reduces the scheduling energy waste. Precisely, it eliminates useless transitions by moving in one orientation from a scheduling state to another, then it delays the repeated CRA tests by predicting the further ones.

On an other hand SRA determines redundant nodes with a very low cost. In fact, we prove that a sensor is redundant if a sufficient number of its neighbors belong to well known sub-regions in its sensing disk. Two new enhancements of SRA, denoted (SRA-Rot) and (SRA-Rot-k_{lmax}), respectively, are also described. Finally, simulation results confirm that the EACP protocol merging the stable-predictive scheduling SPEC and the low-complexity redundancy algorithms SRA, outperforms existing well-known EACPs, in terms of energy saving, network lifetime and coverage preservation.

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Chapter 1

Introduction

1.1 Problem Statement and Motivations

A wireless sensor network (WSN) is composed of low-powered nodes, able to sense phenomena, process data and communicate with each others. WSNs applications include battlefield surveillance, environmental monitoring, structural engineering and so on. Most of these applications use a large-scale deployment, where sensors are randomly spread across a Field of Interest (FoI) [4]. Energy efficient design for extending system lifetime, without sacrificing services, is one important challenge in the design of a wireless sensor network [60].

One important issue in WSNs is the coverage problem. It describes how well a sensing field is supervised by sensors. Coverage strategies vary according to what is monitored: a target (static or mobile) or a region such as each location should be covered by at least k sensors, with $k > 1$ for many applications (k-coverage). Like many other services in WSNs, coverage protocols strictly depend on the sensors' energy level. Thus, coverage protocols should be energy-efficient to prolong the lifetime of sensors and hence extend the network operational lifetime.

Generally, Coverage protocols need simultaneous activation of sensors, especially in k-coverage scenarios. Thus, some sensors may be redundant because of overlapping between nodes' region. To overcome this drawback, most energy-efficient coverage protocols (EACPs) employ jointly two algorithms: A *Coverage Redundancy Algorithm (CRA)* and a *Scheduling Algorithm.* The former determines redundant sensors, while the latter is subsequently run to either eliminate them or periodically plan their activity (active or sleep). Most EACPs in the literature (e.g. [6, 75, 126, 15, 51]), operate as follows: Initially, the sensor, in the scheduling algorithm, is at an initial state during which it discovers its neighborhood, then a CRA is executed to identify the first state transition either to the active state or the sleep state. Thereafter, the CRA is periodically re-called to check the redundancy at each scheduling round, the sensor swings continually between the two states until the energy expiration.

Although the previous scenario is shared between several EACPs and claimed to be an energy-efficient one, it has several shortcomings, namely:

1. **The repetitive transitions between scheduling states:**

   The switch between states in most scheduling algorithms is frequent and dynamic. A sensor may uselessly perform a sequence of switches to finally find out that it should simply remain in its initial state. This situation may considerably increase the communication overhead, as the sensor should continually notify the neighborhood. Furthermore, switching a radio on and off so often may also result in more energy consumption than leaving the transceiver unit in Idle mode [28, 26].

2. **The frequent executions of the CRA:**

   The sensor may also lose further computation energy due to frequent CRA executions. In fact, the CRA is imperatively executed at the beginning of each round and after each notification to be aware of the next scheduling transition.

3. **The CRAs' complexity problem**

   Besides the energy wasted due to their frequent executions in each scheduling round, most CRAs also consume a great amount of energy during their execution. In fact, many iterative treatments should be performed to determine the overlapping rate shared between sensing disks. most CRAs are costly algorithms ([75]($O(n^2log(n))$),[55]($2O(n^2log(n)$),[111]($O(n^3)$)).

In this thesis, we focus on the design of a new EACPs, with a new scheduling algorithm and a new CRA, that settle the previous shortcomings. The major contributions made in this thesis are summarized as follows:

1.2 Contributions

- A first taxonomy is proposed. Its objective is to provide a better understanding of the assumptions and features of coverage protocols in WSNs.

- A second taxonomy is proposed. It is devoted to a special class of coverage protocol which includes energy-aware coverage protocols (EACPs). specifically, we classify in this taxonomy, the energy strategies applied to preserve energy in EACPs.

- The Proposition of a new scheduling algorithm called SPEC (Stable and Predictive Energy-efficient Coverage Scheduling) which reduces the scheduling energy waste and extends the coverage lifetime as well. SPEC removes useless transitions from the scheduling strategy and prevents the run of unnecessary CRAs.

- The Proposition of a new CRA, denoted SRA (Sector Redundancy Algorithm). SRA can accurately determine redundant sensors with a linear running time complexity (only $O(n)$). We prove that a sensor is redundant if its neighbors belong to particular sub-regions within its sensing region called (*Flower Areas (FAs)*).

- A second version of SRA, denoted SRA-Rot (Sector Redundancy Algorithm with Rotation), is proposed. In SRA-Rot, all possible FAs are considered to accurately decide about the sensor redundancy. Indeed, a logical sensing disk rotation is performed to browse all possible FAs.

- A third version of SRA, denoted SRA-Rot-k_{lmax}, (SRA with Rotation and Local Maximum Coverage Degree), is proposed. returns an additional information, compared to SRA and SRA-Rot, which is the local maximum coverage degree k_{lmax} provided by each sensor of the FoI. The knowledge of k_{lmax} helps to smoothly derive the coverage degree of the entire FoI.

- The EACP based on the stable-predictive scheduling SPEC and the low-complex redundancy algorithm SRA (or its successors) and called SRA-SPEC, is proposed. It inherits the advantages of the previous two proposed protocols in terms of energy conservation, connectivity and coverage quality.

1.3 Thesis Organization

The organization of this thesis is as follows:

In Chapter 2, we give an overview of the coverage problem in WSNs, including almost coverage assumptions, parameters and objectives found in the literature. A taxonomy which analyses the characteristics of many recent coverage protocols is also presented in the chapter.

In Chapter 3, we present the energy strategies applied to preserve the coverage energy in EACPs and propose a taxonomy of these strategies.

In Chapter 4, we propose a new stable and predictive scheduling, where transition and CRA execution frequencies, are considerably reduced.

In Chapter 5, we presents the low-complex redundancy algorithm (SRA), and its successors SRA-Rot and SRA-Rot-k_{lmax}, respectively. The EACP issued from the combination of SRA and SPEC is also presented in this Chapter.

To conclude, Chapter 6 summarizes the main contributions of this thesis and discusses potential future work directions.

Chapter 2

Coverage In Wireless Sensor Networks: An overview

2.1 Introduction

A WSN is composed of sensors deployed in different geographical locations. Sensors monitor physical phenomena then send the monitoring report to one or more sinks. A sink is regarded as an interface between the sensor and the external word.

Coverage in WSNs describes how well each point is covered by sensors. Many coverage protocols have been proposed in the literature, some are centralized and other are distributed. Centralized protocols (e.g. [6, 41, 17]) run on a sink, require global information on the whole network and have low adaptability to network changes. Conversely, with distributed ones (e.g.[104, 14, 111, 75]), the decision process is performed locally and simultaneously carried out by each sensor node.

Either centralized or distributed, coverage protocols depend on their specific assumptions. In fact, each protocol has its own sensing model (binary, probabilistic or exposure), acquires its own coverage quality (i.e. the coverage percentage) and type (the object to cover). As a consequence, coverage algorithms seem to be very heterogeneous. In this chapter, we provide an overview of the coverage problem in WSNs including almost coverage assumptions, parameters and objectives found in the literature. A taxonomy which analyses the characteristics of many recent coverage protocols is presented then followed by a discussions about the coverage problems in WSNs.

The remainder of this chapter is organized as follows: Section 2.2 provide preliminary definitions. Section 2.3 presents sensing models in WSNs, while Section 2.4 and Section 2.5 describe the coverage type and the coverage quality, respectively. Section 2.6 is devoted to the coverage optimization objectives and Section 2.7 provides a new coverage protocols' classification. Finally, Section 2.8 concludes the paper.

2.2 Definitions

In what follows, we provide some basic notions and definitions used throughout this chapter.

Definition 1 (**Sensing range**)**.** *The sensing range of a sensor* s_i *is modeled as a disk of radius* r_i *including its boundary. A point* p *in a field* A *is said to be covered by a sensor* s_i *if and only if* $\delta(s_i, p) \leq r_i$*, where* $\delta(s_i, p)$ *is the Euclidean distance between* s_i *and* p*.*

Definition 2 (**Communication range** [75])**.** *The communication range of a sensor* s_i *is modeled as a disk of radius* R *including its boundary. A sensor* s_j *is said to be a neighbor of* s_i *if and only if* $\delta(s_i, s_j) \leq R$*, where* $\delta(s_i, s_j)$ *is the Euclidean distance between* s_i *and* s_j*.*

Definition 3 (**Homogeneous and Heterogeneous sensors** [75])**.** *Two sensors* s_i *and* s_j *are homogeneous if they have the same sensing and communication capabilities; i.e.* $r_i = r_j$ *and* $R_i = R_j$*. Otherwise,* s_i *and* s_j *are heterogeneous.*

Definition 4 (***Coverage***)**.** *A location p(x, y)*$\in A$ *is said to be covered by a node* $s_i \in S$ *if* $(x - x_i)^2$*+*$(y - y_i)^2 \leq r^2$*.*

Definition 5 (k***-Coverage***)**.** *A location p(x, y)*$\in A$ *is said to be k-covered, or have a coverage degree of k, if it is covered by at least k nodes.*

Definition 6 (***Connectivity***)**.** *Two nodes* s_i *and* s_j *can directly communicate with each other if their Euclidean distance is less than a communication range R. Specifically,* $\delta(s_i, s_j) \leq R$ *[111]*

Definition 7 (k***-Connectivity***)**.** *A WSN is said to be k-connected if there is at least k communication paths between any pair of sensors [6].*

Definition 8 (***Redundancy or Ineligibility***)**.** *We refer to a node* s_i *as a redundant (or ineligible) node if each point within its sensing area is also covered by other active nodes.*

Definition 9 (***Network lifetime***)**.** *The network lifetime is the time there is at least a certain fraction β of surviving nodes in the network [19, 36, 54];*

2.3 Sensing models in WSNs

Based on different event scenarios, many sensor models have been proposed in the literature. Sensor coverage models measure the sensing capability function to cover an object [107]. Three sensing coverage models exist, namely : *binary model*, *probabilistic model* and *exposure model.*

Binary model

The binary (or Boolean) sensing model is the most used sensing model in WSNs [68]. It is a simplification of the coverage problem where the sensing area of a sensor is assumed to be a disk with a fixed sensing range. When an event occurs within a sensor's sensing range, it is well monitored by the sensor, hence the coverage quality is then equal to one; otherwise, it is equal to zero. Different sensor types are assumed to have different sensing ranges and can adjust them. Some researchers (e.g. [18, 110]) argue that a sensor consumes more energy when it uses a larger sensing range. To reduce the energy consumption, the sensor can adjust the use of its sensing ranges.

Probabilistic model

The binary sensing model is suitable for sensors to detect events whose quality of surveillance is only affected by sensing distances, like humidity and temperature. However, this is sometimes may not be able to capture the stochastic nature of signals. In the real world, the sensing capabilities of sensor nodes are usually dependent on environmental factors and signal propagation characteristics. Therefore, the sensing model based on the probabilistic assumption may be more realistic to capture the actual sensing capability of sensors [68]. The sensing capability of a sensor i for a location u is expressed by a probability function $P_i(u)$. The detection probability, $P(u)$ is modeled by:

$$P(u) = 1 - \prod_{i=1}^{n}(1 - P_i(u)) \tag{2.1}$$

where n is the total number of sensors.

Exposure model

The Exposure Model, also known in the literature as *the Worst* and *Best Model*, quantifies the quality of coverage by finding areas of lower and high surveillance when mobile targets move [42].

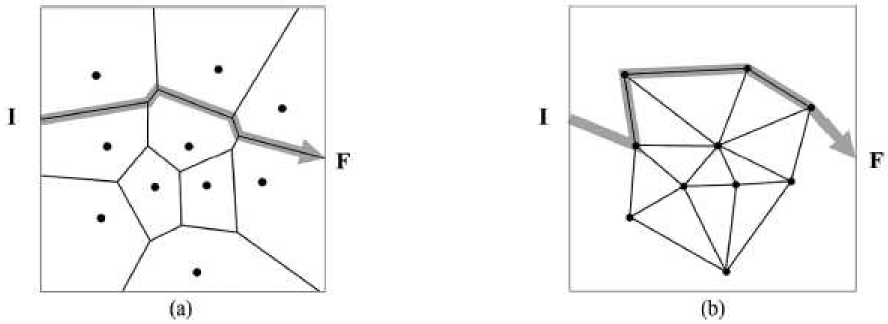


Figure 2.1: Examples of: (a) MBP; (b) MSP. I and F are the source and destination points, respectively.

Let S denotes the set of sensor nodes and P a path connecting an initial location I and a final location F (Figure 2.1).

The *Breach* and the *Support* of a path, two elementary definitions in the exposure model, are given as follows:

Definition 10 (**Breach of a path**). *The breach of a path P connecting I and F is defined as the minimum Euclidean distance from P to any sensor in S. For every point on P.*

The Euclidean distance between the point and its nearest sensor is measured, then take the minimum among these distances. The one with the maximum breach value is called a *maximal breach path* (*MBP*).

Intuitively, there are infinitely many paths connecting I and F, and exhaustive search for the maximal breach path is not possible. The authors in [81] provides a geometric division of the sensor field and argue that, at least, one maximal breach path lies on the of a Voronoi diagram. A Voronoi diagram is a partitioning of a plane into regions based on distance to points in a specific subset of the plane. That set of points (called sites) is specified beforehand, and for each seed there is a corresponding region consisting of all points closer to that seed than to any other. These regions are called Voronoi cells. The Voronoi diagram of a set of points is dual to its Delaunay triangulation [43].

Definition 11 (**Support of a path**). *The support of a path P connecting I and F is defined as the maximum Euclidean distance from P to the closest sensor in S.*

For every point on P, we measure the Euclidean distance between the point and its nearest sensor and then take the maximum among these distances. Among all the paths connecting I and F, the one with the lowest support value is called a *maximal support path* (*MSP*). Authors in [81] argue that at least one MSP lies on the edges of the Delaunay triangulation.

2.4 Coverage type in WSNs

According to the monitored object , coverage in sensor networks can be classified into three types, namely, *target coverage*, *barrier coverage* and *area coverage* (Figure 2.2).

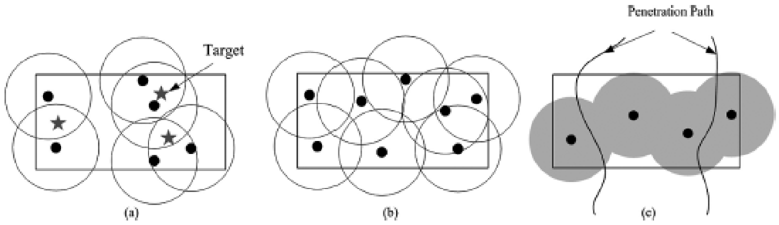


Figure 2.2: Examples of (a): target coverage; (b): area coverage; (c) barrier coverage.

2.4.1 Target coverage

Target Coverage is considered as the ability to monitor a set of discrete points. These points can be used to represent some physical targets in the sensor field the missile launchers in a battlefield [107]. A large number of sensors are randomly scattered to cover targets. Assuming that every sensor is able to monitor all targets within its sensing range, the requirement is that every target must be monitored all times by at least one sensor (1-coverage) [2]. In order to cover these targets, sensors can be manually deployed or randomly placed in the sensor region. Some problems relevant to the target coverage are presented as follows:

Node placement in deterministic deployment

The locations of the targets to be monitored are assumed known before placement.

Let δ_{ij} denote an indicator function of whether a target j can be covered by a sensor located at the site i, that is,

$$\delta_{ij} = \begin{cases} 1, \ if\ target\ j\ is\ covered\ by\ a\ sensor\ located\ at\ site\ i, \\ 0, otherwise \end{cases}$$

The problem of placing the least sensors to cover all targets can be formulated as the following Integer Linear Programming (ILP) problem.

$$\text{maximize} \sum_{i=1}^{I} x_i \tag{2.2}$$

$$\text{subject to} \sum_{i=1}^{I} \delta_{ij} \geq 0, j = 1, \ldots, J. \tag{2.3}$$

$$x_i \in \{0, 1\}, \quad i = 1, \ldots, n. \tag{2.4}$$

Various generalization of the previous ILP problem, which describe different scenarios, have also been proposed. For instance, when the deployed sensors have different costs and coverage capabilities (e.g. [130]), when the distance between any pair of sensors should not be too close (e.g. [93]), or when it is required that each target is covered by at least k sensors (e.g. [92, 47]) or k connected sensors (e.g. [128, 56])

Maximize target coverage lifetime in random deployment

In random deployment, sensors can be divided into *subsets* or *set covers*, each of them can cover all targets. Furthermore, some sensors may be additionally selected to act as relaying nodes to maintain the network connectivity. The cover sets will be recursively scheduled to operate for a certain period [2, 119, 39, 125, 16]. In [16] for example, every target must be monitored at all times by at least one sensor and every sensor is able to monitor all targets within its operational range. One method for extending the sensor network lifetime is to divide the set of sensors into disjoint sets such that every set completely covers all targets. Assuming that n sensors $s_1, s_2, \ldots, s_n$ are deployed to monitor m targets $T_1, T_2, \ldots, T_m$. The goal is to divide the sensors into a maximum number of disjoint sets, such that every set completely covers all the target points. Figure 2.3 shows an example with 4 sensors s_1, s_2, s_3, s_4 and three targets T_1, T_2, T_3.

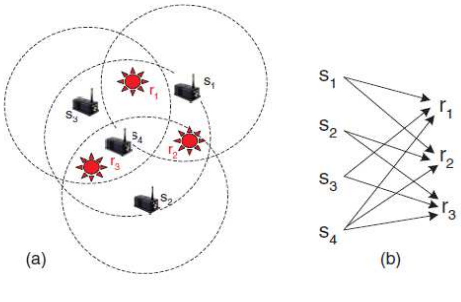
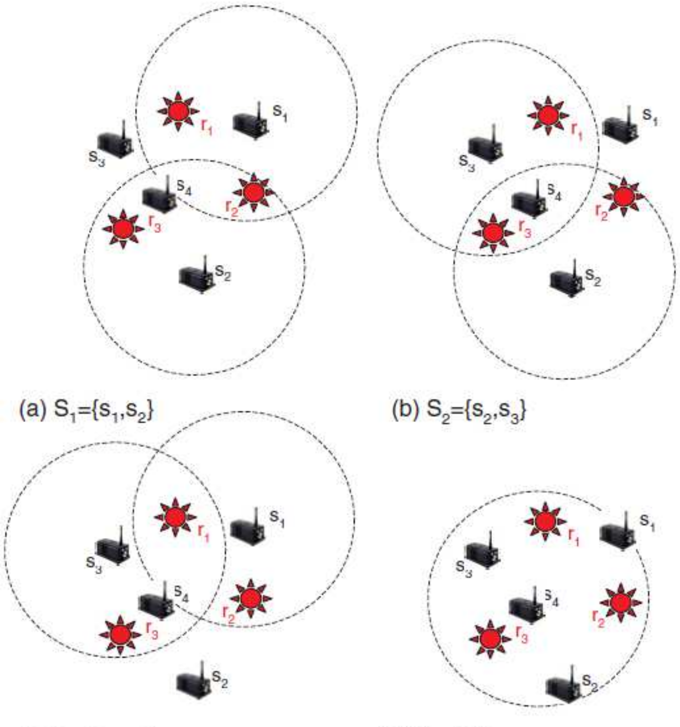


Figure 2.3: Target monitoring.

If all sensor nodes have the same remaining energy (a unit time of 1) and if all sensors are active continuously, then the network lifetime is 1. If the sensors are divided in maximum disjoint sets $S_1 = \{s_1, s_2\}$ and $S_2 = \{s_3, s_4\}$, then the network lifetime is 2. The problem to find the disjoint sets is NP-complete; The same authors in [17] improved the scheduling scheme by allowing every sensor to be a part of one or more than one set and by allowing the sets to be operational for different time intervals. Figure 2.4 illustrates the sets in this case: $S_1 = \{s_1, s_2\}$, $S_2 = \{s_2, s_3\}$, $S_3 = \{s_1, s_3\}$, and $S_4 = \{s_4\}$. This organization results in a network lifetime of 2.5. The maximum set cover is also is NP-complete; authors proposed an heuristic to resolve it.



(a) $S_1=\{s_1,s_2\}$ (b) $S_2=\{s_2,s_3\}$

(c) $S_3=\{s_1,s_3\}$ (d) $S_4=\{s_4\}$

Figure 2.4: Set covers in target coverage.

2.4.2 Barrier Coverage

The goal of barrier coverage is to detect subjects crossing a long belt shape field. If C_1 and C_2 are two parallel curves with a separation width w, the region between C_1 and C_2 is said a belt region with a width w [113]. A WSN deployed in a belt region provides a barrier coverage, if all crossing paths within the belt intersect the sensing disk of at least one sensor [113]. Some problems relevant to the barrier coverage are presented as follows:

Built k-barrier coverage

Intrusion detection is the most important application of barrier coverage, but many work do not focus in detecting the object movement at every point on its trajectory but only at a few distinct sensors. For instance, Kumar et al. [65] asked whether the belt provides k-barrier coverage or not?. They suggest to use a global coverage graph to check this property. A coverage graph CG = (V, E), where V represents sensors and E the edges between them. An edge in E exists between two nodes of V, if their sensing regions overlap. In addition, they define two virtual nodes, s and t that indicate the left and the right of a belt. The researchers prove that a belt region is k-barrier covered if there exist k node-disjoint paths between the two virtual nodes s and t in the coverage graph.

Find the best crossing paths

A crossing path is a path which enters the sensor field from one side and leaves the sensor field from the other side. The objective is to find one crossing path such as every point on it satisfies a predefined coverage requirement. The exposure model, already defined in subsection 2.3, relies on the detection of such a path.

2.4.3 Area Coverage

Despite to cover a few targets like in target or barrier coverage types, the objective of area coverage is to cover the entire FoI. The area coverage is always discussed for a continuous space. Thus, it is usually hard to be transformed to a discrete space problem, which makes the area coverage problem more difficult to solve [107]. The problem of area coverage, also called *blanket coverage*, or *full coverage* is related to the traditional art gallery problem (AGP)[3]. The AGP determines the minimum number of cameras that can be placed in a polygonal environment, such that every point is monitored [45]. Similarly, area coverage tries to deploy a minimum number of sensor to cover each point of the region. Generally, all sensing disks in a region should be covered by at least k active sensors (k-coverage). Each subset of the active sensors operates for a certain interval, and then is scheduled to another subset, which aims at maximizing the network lifetime. Some problems relevant to the area coverage are presented as follows:

Optimal node Placement

Since all points in the FoI should be covered, the node placement problem in area coverage is more difficult to resolve than in target or barrier coverage. The main idea, in the case of deterministic deployment, is to find a basic placement pattern (e.g, polygon or triangle) that can be repeated to cover the whole sensor field. Researchers (e.g. [6]) tries to find the appropriate *Critical Sensor Density* (*CSD*), which gives an insight on the minimal number of sensors required to complete area coverage.

The analysis of CSD, in a random deployment, starts by giving bounds for the complete coverage probability of a square field A that envelop the sensing disk, then an asymptotic analysis is provided to find the relation between: the CSD and the areas larger than A until reaching all the FoI's area.

Minimum number of active sensors

The main idea of these work is to find a deployment pattern that satisfies three conditions: the network area is k-covered, the sensor nodes are m-connected, and the number of deployed sensors is minimized. In fact, the optimal distance between sensors for three different deployment patterns: triangle, square, and hexagon, is estimated (e.g. [6, 126]). The protocol then chooses the deployment pattern to be used to deploy minimum number of sensors while meeting the coverage and connectivity requirements

Coverage hole

Coverage hole refers to find fields that are not covered by any node [38]. The loss of a node due to failure may not only affect the network coverage but also impact network connectivity. Most works in this context focus on repairing the coverage/connectivity hole by sustaining the pre-failure coverage [133]. Mobile sensors or robots are often used to replace the failed sensors. They move temporarily to the position of the failed node then go back to their original position allowing other neighbors to replace them [103]. Since the mobility of nodes consumes more energy, the protocol suggested by [89] study beforehand the nodes' direction then predict the less costly to reach the failed node. On an other hand, other many work,(e.g. [86, 27, 28]), assume that coverage holes may appear if two redundant sensors go to sleep at the same time [100]. Scheduling algorithms (Section **??**), which plan the sleep and activity timers, provide favorable solutions to this problem.

Redundancy determination and elimination

Redundant sensors may appear in area coverage due to the high sensors density. . Activity scheduling for area coverage maintenance, is used to schedule nodes to be activated alternatively, such that the network operation time may be prolonged and the monitored areas still covered. The question is to determine which sensor should be active, at which time and for how long.

2.5 Coverage Quality

All coverage protocols, whatever their types, target, barrier or area coverage, aims to achieve a good coverage quality. The coverage quality expresses the percentage of objects (targets or sub-regions) that can successfully be covered. In this subsection, we present two kinds of coverage quality, namely, partial coverage and k-coverage.

2.5.1 Partial Coverage

We use partial coverage to state the situation where most of points in the FoI (or some targets) can not be covered with the required coverage degree. Some work (e.g. [121, 51]) have shown that the network coverage lifetime can greatly be prolonged if only partial coverage is preserved. In fact, a sensor, during partial coverage, does not always need to perform frequent redundancy tests. Therefore, computation complexity and energy are greatly reduced.

2.5.2 K-coverage

Ensuring k-coverage for a FoI, is checking whether each of its point is covered by at least k sensors. As it can be seen in Figure 2.5 , the sensing disk parts of all sensors are covered by either one, two or three sensors. The coverage degree k is the minimum among these numbers. The number "1" in Figure 2.5 indicates the minimum coverage degree of the FoI's sub-regions. The entire FoI is then 1-covered. .

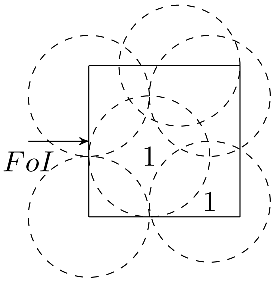


Figure 2.5: The FoI is 1-covered.

Applications requiring k-coverage occurs in situations where a strong monitoring capability is desired, such in military applications. K-coverage can be formulated as a decision problem, the goal is to determine whether every point in the area, or each target in target or barrier coverage, is covered by at least k sensors, hence, k-coverage a difficult and computationally expensive task [24]. Moreover, redundant sensor may appear in k-coverage scenarios, because of overlapping between several sensing disks.

2.6 Coverage Optimization Objectives

Besides enhancing the coverage quality in WSNs, several optimization objectives are proposed to improve the efficiency of the coverage protocols. Each of which is elaborated separately in the following subsections :

2.6.1 Connectivity

After collecting information from the environment in a WSN, sensors should transmit the aggregated data to the base station (or a sink). Indeed, it is important to ensure that every sensor can communicate with the sink directly or by the intermediate of relay nodes. Generally, the network is modeled, in coverage-connectivity scenarios, by as a graph where the communication link between a pair of nodes is an edge, then the connected network implies that the underlying graph is connected. Among the important works in the coverage-connectivity issue, the Coverage Connectivity Protocol (CCP) [104]. It discusses two different assumptions, $R > 2r$ and $R < 2r$, where R and r are the communication and the sensing ranges, respectively. When $R > 2r$, maintaining k-coverage and k-connectivity is equivalent to maintain only k-coverage.

However, when $R < 2r$, CCP cannot guarantee connectivity. Thus, it integrates an existing connectivity protocol like SPAN [22]. CCP and other coverage-connectivity protocols (e.g. [104, 75, 6]) will be detailed in the next chapter.

2.6.2 Fault Tolerance

Fault tolerance is a crucial issue, especially for sensors deployed where they are not easily replaceable, reparable and rechargeable. The failure of, one or several sensors, can paralyze the area coverage unless it was before completely covered. Indeed, The failure of a sensor can cause a coverage hole and even a network partition [24]. Checking sensor failure is necessary, not only for awareness, but also to heal any coverage holes. One intuitive mechanism for fault tolerance is the augmentation of the coverage degree. In fact, There are several reasons for asking a wireless sensor network to be k-covered. First, it could be for the fault-tolerant reason. Second, some special applications, such as tracking or trilateration, may require each point in the sensing field to be at least 3-covered [68]. In the following, we expose some works that investigate the coverage protocols based on fault tolerance issue.

The objective of the work cited in [124] is to restore coverage of the area under unexpected node failure. This approach lets every active node independently select a set of backup covers for its sensing region, and schedule them to check periodically for holes. Backup covers are special sets of sensor's neighbors which can replace them to cover their regions in failure cases. Backup nodes periodically wake up and go to the "PROBING" state. When a backup node discovers a no monitored region, it goes to active state.

In [8], the authors study fault tolerance from a new point of view that is the availability of the system; they select a value of monitoring period t_s that maximizes the availability. In this scheme, nodes collectively decide which ones are not fundamental for sensing. These nodes should be sleeping most of time, and wake up only within the monitoring period t_s in order to replace failed nodes. However, a theoretical method to determine t_s is not specified in [8].

Ammari and Das [7] tried to find a precise relationship between coverage, connectivity and fault tolerance issues. In fact, they define some properties like the *field fault tolerance* η, which is the capacity of a field to remain covered by at least one sensor despite the failure of a certain number of sensors in k-connected network. Koushanfar *et al.* in [64] exposes the problem of fault-tolerant multi-modal sensor fusion for digital binary sensors. The main idea in [64], is to adapt application algorithms and/or operating systems to match the available hardware and the applications needs. The five primary types of resources in WSNs; computing, storage, communication, sensing and actuating, can replace each others in system and application software. For example, if communication bandwidth is reduced and all of the computation power is available, the system can compress data using more computationally intensive compression schemes. On the contrary, when computational power is reduced and communication is fully available, the node can transmit more raw data to other nodes for processing.

2.6.3 Tracking

This aspect concerns, especially, the barrier coverage type (Section 2.4.2), where sensors should cover mobile targets all the time. We address few tracking-related work in the following:

In [74], the authors propose a new paradigm to track the target based on Voronoi diagram considering the tracking accuracy, continuity and coverage hole problem. The proposed algorithm is composed of two modes. In the former, a sleep scheduling is applied to balance the energy consumption and track the channel to check whether its neighbors attempt to communicate with it. In the latter, the k-nearest neighbors are always active to track the target. When the target moves in a polygon of k-order Voronoi diagram, the k nodes keep tracking the target and the other nodes follow their own sleeping schedule to save energy. When the target moves into another polygon, the k-nearest neighbors of the target change.

In [97], the authors propose a probabilistic-based dynamic k-coverage method, where target moving area is covered by at least k sensors and with the least possible probability. This problem is formalized as a binary linear problem, which is classified NP-hard. A heuristic algorithm is proposed to solve this problem.

2.6.4 Energy Efficiency and Network Lifetime Prolongation

Energy efficiency is an important issue in WSNs. In many application scenarios, like coverage, replacing or recharging the batteries of the sensors is impossible when they are deployed in hazardous environments. One method to conserve energy and extend the lifetime is to share the energy consumption between nodes [23, 108]. Coverage vs energy conservation and network lifetime prolongation issues, will be deeply detailed in the next chapter.

2.7 Coverage protocols' classification

Although coverage protocols share the same objective, which is the coverage preservation, most of them are contrasted in their assumptions and constraints; partial coverage vs k-coverage, area coverage vs target coverage, and so on.

Several coverage-related surveys have been proposed in the literature. However, each of them focus on a subset of features at a time, like coverage and connectivity (e.g. [45, 105]), coverage and deployment (e.g. [63]), coverage and energy efficiency (e.g. [82]) and coverage and tracking in (e.g.[114]).

To give a better comprehensive to the coverage problem in WSNs, we provide, in this section, a new taxonomy of coverage protocols with a wide range of features and assumptions as illustrated in Figure 2.6

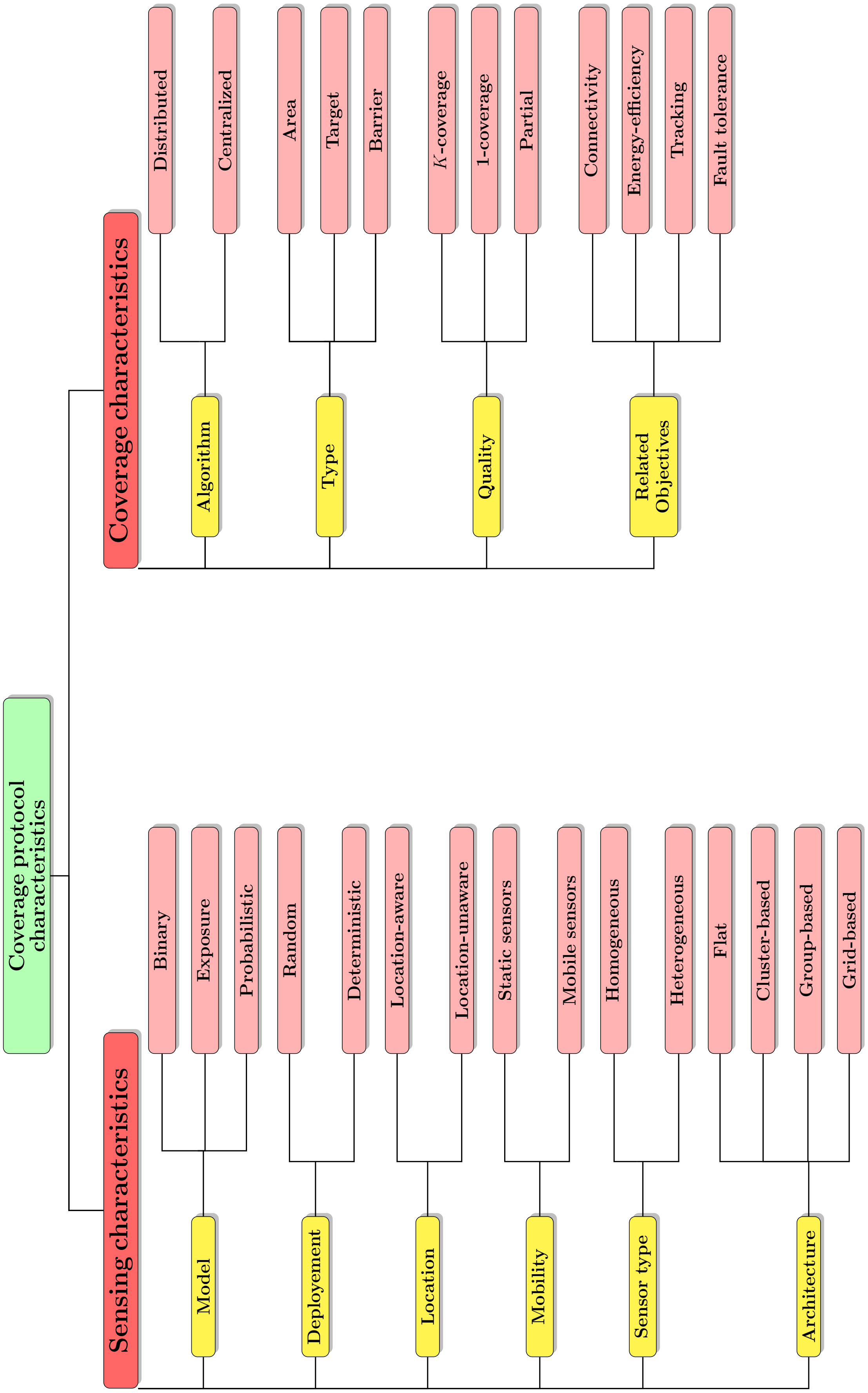


Figure 2.6: Taxonomy of coverage protocol characteristics.

First, we classify the coverage protocol characteristics to sensing characteristics and coverage characteristics. The sensing characteristics include the physical features of the sensor and its network, like the sensing model, the deployment method, the network architecture, and so on. The coverage characteristics include the parameters of the coverage service, like the coverage type and quality and so on. Sensors differs according to their type (homogeneous or heterogeneous), their mobility pattern (mobile, static or directional, having a limited angle of sensing range), their location information (location aware or location unaware), their sensor deployment (random or deterministic), the sensor model (binary, probabilistic or exposure) and the network architecture. This later can be organized into: Flat protocols (e.g. [27, 26]), Grid-based protocols (e.g.[59, 72]), where the regions are divided into virtual grids and every sensor is deployed at the intersection points of the grid. The grid can be square, triangle, hexagon, etc and Cluster-based protocols (e.g. [96, 87]), where nodes in a network organize themselves into groups according to specific requirements or metrics.

On an other hand, the coverage parameters include the coverage quality (1-coverage, k-coverage and partial coverage), the coverage type (target, barrier and area), the coverage algorithm, either distributed and centralized. Finally, coverage parameters include the related optimization objectives, namely, connectivity, energy efficiency, tracking and fault tolerance. Table 2.1 summarizes the previous key features of some coverage protocols cited in this chapter.

Table 2.1: Comparative study of coverage protocols.

		Sensing characteristics			**Coverage characteristics**			
Coverage protocol	**Description**	**Model**	**Deployment and location**	**Mobility, type and architecture**	**Algorithm characteristics**	**Type**	**Quality**	**Optimization objectives**
CCP [111]	Transforms the problem of determining the coverage degree of a region to the simpler problem of determining the intersection points in a region	Binary	Random Location-aware	Static Heterogeneous Flat	Distributed	Area	K-coverage	Connectivity. Energy-efficiency. Fault tolerance.
CAR [17]	Organize the sensors into a maximal number of sets to cover all targets.	Binary	Random Location-aware	Static Homogeneous Group-based	Centralized	Target	1-coverage	Energy efficiency.
YAR [121]	Determines the minimum achieve a partial coverage using a geometric theory	Binary	Random Location-aware	Static Homogeneous Flat	Distributed	Area	Partial	Connectivity.
CPP [75]	provides a complete coverage by checking perimeters	Binary	Deterministic Location-aware	Static Homogeneous Flat	Distributed	Area	k-coverage	Energy-efficiency.
CERACC [6]	Achieve coverage by dividing the region into sectors.	Binary	Deterministic Location-aware	Static Homogeneous Grid-based	Centralized	Area	k-coverage	Connectivity.
PREDP [51]	Adopts a probabilistic approach to determine the partial	Binary	Random Location-aware	Static Heterogeneous	Distributed	Area	Partial	Energy-efficiency.

Table 2.1: Comparative study of coverage protocols (Continued.).

Coverage protocol	**Description**	**Sensor model**	**Sensor deployment and location**	**Sensor architecture, type and mobility**	**Coverage algorithm characteristics**	**Coverage type**	**Coverage quality**	**Optimization objectives**
	of redundancy degree			Flat				
MoBibar [101]	provides the maximum achievable barrier coverage by re-positioning mobile sensors.	Binary	Deterministic Location-aware	Mobile Homogeneous Flat	Distributed	Barrier	Partial	Connectivity.

2.8 Conclusion

In WSNs, many new protocols have been proposed to solve the coverage problem. We presented, in this chapter and reviewed known and recent a these protocols. In fact, for each coverage type we exposed its associated problems. Although most of coverage protocols have contrasted assumptions and features, they aim all to preserve coverage with minimum energy consumption. In the next chapter, energy mechanisms to maintain coverage in WSNs will be discussed in more details.

Chapter 3

Coverage and Energy Preservation Issues In Wireless Sensor Networks

3.1 Introduction

The energy consumption problem in WSNs take several aspects. In fact, sensors have limited energy resources, they are usually deployed in hostile environments where recharging or replacing them may be impossible. Moreover, they are densely deployed in a FoI, where there is a possibility that more than one node cover the same sub-region. Thus, the data sensed by multiple nodes may have a certain amount of correlation or redundancy[82]. In order to sustain sensors to run for a long period of time with limited energy capacity, it is crucial to design energy efficient protocols that allow nodes to accomplish their tasks (sensing, transmitting, computation, listening) with a moderate energy depletion.

Many surveys have investigated the coverage problem in WSNs, however, very limited works have investigated the energy conservation mechanisms considered during coverage (e.g.[82, 11]). This chapter explores this issue.

The remainder of this chapter is organized as follows: Section 3.2 reviews the Energy consumption in WSNs. Section 3.3 presents the Energy-Aware Coverage Protocols (EACPs). Section 3.4 explains the EACPs based on redundancy control and periodic distributed sleep-scheduling (EACPs-RS) and Section 3.5 give a discussion about EACPs. Finally, Section 3.6 concludes the chapter.

3.2 Energy consumption in WSNs

The sensor lifetime depends on the energy amount of its battery, consumption before and during deployment should be well controlled in order to increase the network lifetime. In this section, we present the several operation modes of a sensor and the sources of energy consumption in wireless networks. A typical sensor node can be in one of four distinct modes [122]: *Transmit*, *Receive*, *Idle*, or *Sleep.* a node in *sleep* mode is not able to detect any signal because the majority of its components are turned off. This mode consume a very low power consumption. When a radio is on and it is neither transmitting nor receiving, a sensor is said to be *idle* . In most cases, operating in *idle* mode results in significantly high energy consumption, because the radio electronics have to be turned on and continually decode radio signals, even noise, to detect the presence of incoming packets [122]. In the *Transmit* mode , the node can transmit packets using wireless channel. This state consumes the highest amount of energy of the four states. In the *receive* mode, the power is only slightly lower than the transmitting mode. Nodes consume energy when sensing, processing, transmitting or receiving data. Measurements have shown that among of these major activities, a sensor expends maximum energy in data communication, involving transmission, reception, and being idle. In addition, the transition between modes is not energy neglected, it is energy and time consumer[28]. On an other side , a great amount of energy wasted in states that are useless from the application point of view, such as [122]:

- **Overhearing:** meaning the node receive packets that are destined to other nodes. Indeed, in wireless networks, when a node transmits a packet, all nodes in its communication range receive this packet even if they are not the intended destination.

- **Collision:** collisions occur when multiple packets get transmitted simultaneously which magnifying the signal interference. All packets that cause the collision have to be discarded and the re-transmission of these packets is required.

- **Control packet overhead:** the third source is the overhead of sending and receiving medium access control packets.

- **Idle listening:** energy dissipation happens when a node is listening for possible traffic.

- **Interference:** each node located between transmission range and interference range receives a packet but cannot decode it.

- **Wireless noise:** in which packets get corrupted and need to be re-transmitted or to increase the transmission power to overcome the noise level.

- **State transitions:** frequent switching between modes especially switching from sleep mode to an active mode leads to significant energy consumption as shown in Table 3.1.

Table 3.1: Typical values of energy costs relevant to various cards.

Card	$P_{Tx}(mW)$	$P_{Rx}(mW)$	$P_{Idle}(mW)$	$P_{Sleep}(mW)$	$P_{Transition}(J)$
Cabletron	1400	1000	830	130	1.328
Lucent Wavelan	1327.2	966.9	843.7	66.3	0.6
Cisco Aironet 350	1850	1590	1150	140	$0.19 \sim 0.6$

3.3 Energy-Aware Coverage Protocols (EACPs)

EACPs or *Energy-Aware Coverage Protocols*, are coverage protocols aiming to conserve as possible the sensors' energy while maintaining a sufficient coverage preservation. Coverage process require the activation of a great number of sensors, thus the consumption of great amount of energy especially when covering regions (area coverage) or requiring a k-coverage fulfillment. We explore in this section the different energy-saving mechanisms adopted by EACPs to conserve coverage with a lightweight energy consumption.

Two mechanisms collaborate in the design of EACPs, namely: *The topology management mechanism* and *The sleep-scheduling mechanism* (Figure 3.1).

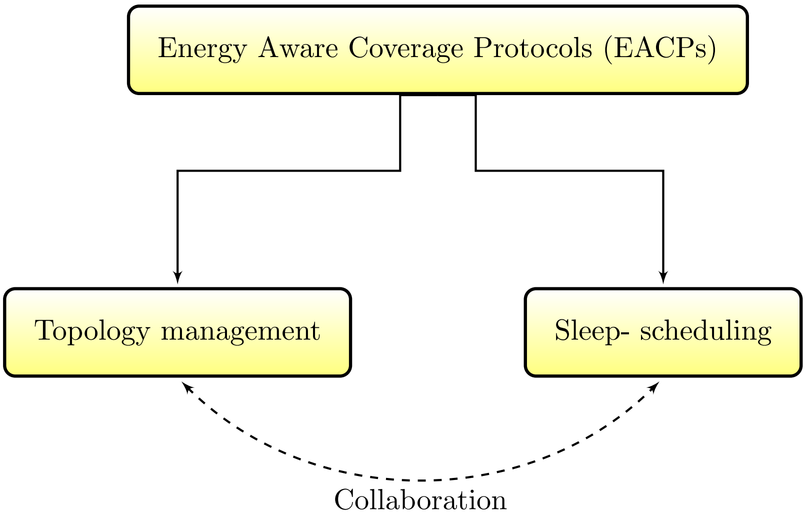


Figure 3.1: The collaboration in the design of EACPs.

The topology management exploits the network density while conserving energy and extending the network lifetime. To this end, it keeps only a subset of nodes in active mode and turns off redundant ones, while the sleep-scheduling mechanism defines a coordinated sleep/wake up to schedule the sensors' activity. On an other words, the sleep-scheduling mechanism can be accomplished only when the topology mechanism define redundant nodes. Hence, the energy consumption is reduced at two levels:

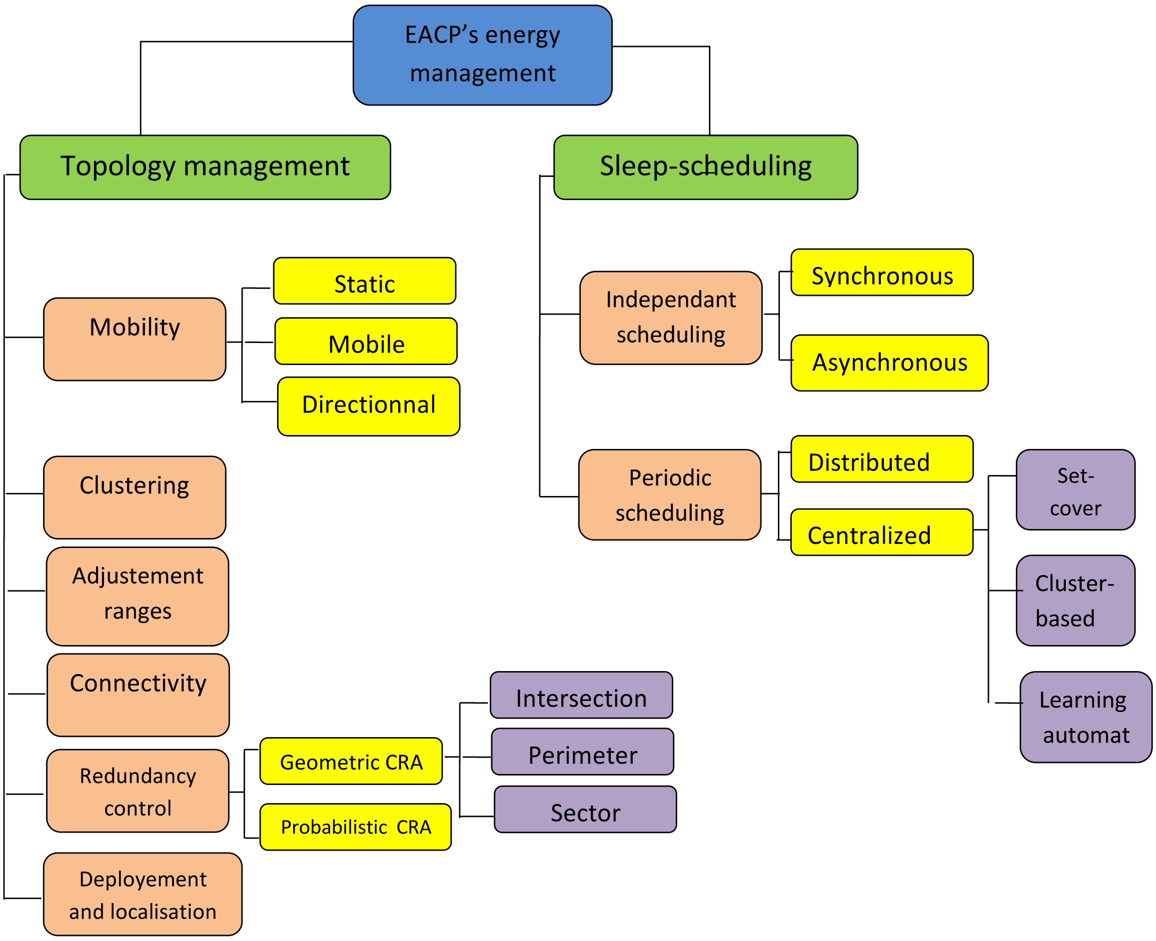


Figure 3.2: Taxonomy of EACPs' energy management.

first, by locating redundant nodes and eliminating them, second, by balancing the energy depletion between the rest of sensors (the active ones) at each scheduling round. We propose, in this section, a taxonomy of EACPs that distinguish six techniques in the topology management mechanism, namely: mobility, clustering, adjusting sensing ranges, connectivity, redundancy control and deployment and localization. Similarly, we distinguish two techniques in the sleep-scheduling mechanism, namely: independent and periodic schedulings. The proposed taxonomy is illustrated in Figure3.2

3.3.1 Topology Management

Once the sensors are deployed in the sensing region, they form a communication network, which can dynamically change over time depending on the topology of the geographic region. The continual changes in the network topology should preserve both the network coverage and connectivity. Formally, the topology management is defined as the reorganization and management of node parameters (i.e. sensing ranges, models, types) and the sensor state (i.e. active and sleep), to extend the network lifetime while preserving its coverage and connectivity.

Mobility

Mobile nodes can be used to solve the coverage hole problem, already cited in Section 2.4.3 The coverage hole refers to find regions that are not covered by any sensor of the network. In fact, several mobile sensors adapt their positions in order to fill up coverage holes and eventually increase the area coverage with the minimum number of sensors [31, 62]. This technique is called Mobile Deployment Technique (MDT) and it is NP-complete with many conflicting objectives. Hence, centralized evolutionary approaches are often used to solve it [9, 61].

Besides covering holes, mobile sensors, in barrier coverage type, can also be employed to construct k distinct complete barriers and hence provides k-barrier coverage as done in MobiBar [101]. Assuming that all sensors are mobile in MobiBar, the goal is to achieve a final deployment that provides the maximum barrier coverage by re-positioning the mobile sensors. MobiBar assumes that nodes in adjacent barriers can communicate and each barrier has a priority which decreases as the distance between the baseline (which is the line that is parallel to the border of the network area) and the barrier increases. Mobile are re-positioning until a single connected barrier is constructed.

Clustering

Cluster architecture is composed of Cluster Heads (CHs) and ordinary sensors. Clustering techniques can improve energy efficiency by two ways: First, by reducing the communication range inside the clusters which requires less transmission power, second by enabling to power-off some nodes within the clusters while CHs ensure data forwarding. The most famous clustering-based routing protocols are LEACH [54] and TEEN [79]. For example, a cluster-based coverage protocol is proposed in [20]. It computes a near-optimal network configuration in which each sensor can be activated, put in sleep mode or promoted as a CH. The authors in [20] discusses how to compute the cluster size and how to identify the CH and active nodes to fulfill the most energy-efficient coverage achievement. Nevertheless, [20], like the most clustering coverage protocols [58, 118, 20], focus more on selecting the optimal set of CHs to reduce or balance the energy consumption of a given network, while how to cover the network area with realistic energy models, remains less investigated

Adjusting Sensing Ranges

Adjusting sensing ranges is another way to manage the network's topology. Instead of transmitting at the maximal power level, each node can choose a lower transmission power. In fact, the transmission range reflects the maximum distance at which a sender can reach a nearby receiver. The longer the range is, the higher the power consumption would be [123]. Although both coverage problem and adjusting ranges techniques have been studied separately, only a few protocols considered them in a joint way (e.g. [116, 80, 57]). The main goal, in coverage-aware context, is to reduce the sensing range of the active sensors, while maintaining the coverage requirements. This method has a double impact; it reduces the energy consumption and decreases the MAC-layer interference [17].

Connectivity

As already introduced in the previous chapter, satisfying only the network coverage without connectivity may paralyse the data transmission. In fact, several works have investigated the coverage-connectivity in area, target and barrier coverage types issue.

Based on the confident information coverage model, the authors in [117] study the sensor placement problem to achieve both coverage and connectivity. In [117], the confident information coverage model is defined as the ability to cover all cells in the whole grid. Indeed, the authors suppose that the sensing field is divided into square grid cells, each with equal unit area, and sensors can be only placed at the center of each grid cell, the objective is to place the minimum number of sensors to form a connected network and to provide confident information coverage for all of the grid points. They formulate then resolve the sensor placement problem as a constrained optimization problem.

In [127], a distributed connected target k-coverage algorithms are proposed. The main idea is to generate particular cover sets able to monitor the maximum number of targets at a time. The proposed algorithm needs to favor sensors that have more available energy than their neighbors, then to promote sensors that can cover remaining targets; i.e. which are not already covered in previous stages.

In 3D topology, [94] presents a novel algorithm for self-deployment of nodes in underwater acoustic sensor networks assuming that the nodes are randomly dropped to the water. The idea of the algorithm is based on calculating an optimized depth for each node, in such a way possible sensing coverage overlaps are minimized and the connectivity of the final topology, is always guaranteed.

For instance, in target coverage type, both 1-coverage and 1-connectivity requirements should be accomplished; each target should be covered by at least one active source; and each source can find one route to the sink. In other words, each set cover should form a *relays tree (RT)*. This problem is called *The Maximum Cover Tree (MCT)* Problem and it is NP-complete. Again, greedy algorithms are proposed to solve it (e.g. [91]).

Redundancy Control

The redundancy is the possibility to obtain information for a specific location from different sources [33]. In random deployment cases, many nodes may drop very close to each others, this situation can provide a redundancy in network coverage and connectivity. For many applications in WSNs [103, 89], redundant sensors are not tu but re-deployed to fill coverage voids in the monitored field. Eligibility algorithms or coverage redundancy algorithms (CRAs) are algorithm responsible to determine redundant nodes in WSNs. They generally evaluate the amount of overlap between sensors, then deduce redundant ones. This evaluation is based either on geometric implementation methods (e.g. [111, 29, 30]), or on probabilistic (analytical) ones (e.g.[15, 49, 102, 67]). The geometric method involve area calculation to quantify the amount of overlapping between nodes. We distinguish three methods to estimate the overlap: *the intersection*, *the perimeter* and the *sector* methods. The amount of overlapping is quantified by checking the coverage of intersection points in the intersection method, the coverage of each perimeter around the sensing disk in parameter method and the coverage of some parts of the sensing disk (sectors) in the sector method.

Deployment and Localization

Sensors deployment can be defined as the process of determining the optimal location, such that the coverage requirement is met[38]. Sensors can be deployed in deterministic or random manner. The former is suitable for known areas, while the latter is appropriate when sensors are deployed in unknown areas with a high density. As sensors are randomly scattered in most practical situations but it is difficult to find a random deployment strategy that minimizes cost, reduces computation and communication, and provides a high degree of area coverage [45, 55].

Ensuring accurate deployment depends also on sensors location and the detection sensing range. Most of the coverage protocols assume that the sensors location information is perfectly accurate. Unfortunately, none of the existing GPS-free localization techniques can provide such accurate information [69]. Hence, many localization protocols have been proposed to enable static or mobile sensors to determine their positions without relying on GPS (e.g.[5, 70]). Location protocols rely in this case on the the network connectivity to estimate nodes' position [37], or they suppose that nodes are equipped with a specific measurement device to measure the distance or the angle between themselves and other regular sensors with unknown locations [5].

3.3.2 Sleep-Scheduling

Sleep-Scheduling, also called duty cycling mechanism, defines coordinated sleep/wake-up schedule among nodes in the network. This mechanism reduces significantly the energy consumption of sensor nodes as it keeps nodes active only when there is network activity; i.e. it aims to minimize the number of active nodes and balance the energy consumption between nodes. An optimal scheduling scheme ensures that only a subset of nodes are active at any time, while satisfying both coverage and connectivity requirements. Formally, the design of a sensor activity scheduling scheme should answer the following question: How to determine which sensors are active at which time and for how long?[107]

Sleep-scheduling schemes can broadly classified into tow classes, namely: *Independent Scheduling* and *Periodic Scheduling.*

Independent Scheduling

It is a simple scheduling to implement, where a sensor decides its activity states independently of its neighbors [46, 1]. Beside its simple implementation, independent scheduling has two main advantages: (1) No location or distance information is required; and (2) no control messages are required [107]. It can be implemented in either asynchronous or synchronous approaches[1]. In the former, the time-line is divided into consecutive rounds with equal length T for each sensor node, but the beginning of the first round is different across nodes; that is, the rounds are not synchronized across sensors. At the beginning of a round, a sensor decides its active state, while the remaining part of the round is the sleep state. In the synchronous approach, the time-line is divided into rounds of equal length and the starting time of every round is considered to be synchronized among sensor nodes.

Periodic Scheduling

Unlike the independent scheduling, a sensor node can schedule its activity based on its neighbors' information. Many of periodic scheduling algorithms have been proposed in the literature (e.g, [34, 27]), yet based on different objectives and assumptions. They are classified into two groups:

- **Distributed algorithms:** The decision process in the distributed scheduling, is localized in each sensor node, and only information from neighboring nodes are needed for the activity decision. It is assumes that the time-line is divided into consecutive rounds. At the beginning of each round, the activity decision is taken according to the CRA's result (sensor is redundant or not), then all sensors are required to be either in active or sleep state at the end of the round. Distributed scheduling algorithms are usually adopted in area coverage type.

  A distributed sleep-scheduling protocol (CMSS) is proposed in [34]. Sensors in CMSS are deployed in a grid cell, they are homogeneous and location-aware.

---

[1] In synchronous approaches, the scheduling starts at the same time for all sensors, while it starts at a uniformly random time in asynchronous approaches.

The main idea of CMSS is to reduce the number of active nodes while ensuring the entire coverage of a region. This is achieved by decreasing the number of redundant sensors that monitor the same cell.

Each sensor in CMSS has two tables: a) a neighbor table, which records the IDs of its neighbors and b) a covered cells table, which records the covered cells and associated sensors covering each cell. At the first round, each sensor broadcast its location information and sensors that receive this information adjust their neighbor table accordingly. In the next rounds, the covered-cells table is updated and the node decides about its activity by applying a random timer technique and checking its covered-cells table.

- **Centralized algorithms:** In centralized scheduling algorithms, a central station (sink, cluster, ..) makes all scheduling decisions then sends the results to sensors which execute them. Centralized scheduling algorithms are usually adopted in target and barrier coverage types and they are classified into three classed, namely: Set cover scheduling, cluster-based scheduling and Learning automaton scheduling.

    1. *Set-cover scheduling algorithms*: A common approach in sleep-scheduling protocols is to classify nodes into disjoint sets of covers such that every set completely covers the targets.

       A GA-based protocol proposed in [40] aims to k-cover a number of targets. Firstly, it determines the optimal cover sensors able to transfer date to the sink. Then, the algorithm forms the covers based on the coverage range of each sensor, the expected consumed energy, the distance to the sink, and the targets positions. Sensors in GA-based protocol are mobile. A cover management method that switches between different set cover was proposed.

    2. *Cluster-based scheduling algorithms*

       Balanced clustering algorithm (BCA) is a distributed clustering protocol proposed in [99]. BCA creates a set of equally balanced clusters, where the coverage of each cluster is approximately the same. It is defined as the union of the coverage areas of all cluster members. In BCA, each sensor calculates its probability of becoming a CH based on its sensing population. Once a sensor node becomes a CH, it uses its sensing population information to put some nodes into sleep mode in order to conserve their energy.

       The authors in [112] developed a cluster-based coverage protocol for target tracking applications. It optimize the positions of mobile nodes to increase the coverage degree. For each cluster, two metrics are calculated: the coverage metric and the energy metric in order to assess the coverage rate and the energy efficiency, respectively. The former is defined as the proportion of the detected area to the whole sensing area, while the later is defined as the lowest cost among all possible communication paths that are from each node to its CH. It is calculated using Dijkstras algorithm. Each CH executes an heuristic that maximize the coverage metric and minimize the energy metric.

The protocol divides the sensor network into fixed number of clusters to perform parallel coverage optimization for all clusters.

3. *Learning automaton centralized algorithms*:

   Coverage with Learning Automate (LA), is a new scheduling method [83, 84, 41, 76]. A LA are designed to select optimal actions (e.g. next state transition in a scheduling scenario) among a set of available actions. In fact, a LA has a finite number of actions that can operate, a probability is associated to each of them. Once an action is applied, the LA generates a reinforcement signal in order to "push" the environment toward the optimal required value. The reply generated by the environment is used by the automaton to update its action probability. Hence, the automaton "learns" to optimally choose actions among its rules [83].

3.4 EACPs based on redundancy control and periodic distributed sleep-scheduling (EACPs-RS)

We sudy, in this section, EACPs-RS, a subset of EACPs based on the redundancy control as a topology management mechanism and on the periodic distributed sleep-scheduling to ensure both coverage and energy conservation (Figure 3.3).

Most area coverage protocols belong to this category of EACPs (e.g. [111, 75, 6, 51]), where a CRA is executed to determine redundant nodes and a sleep-scheduling coordinate the sensors' activity.

Formally, the common behavior, in EACPs-RS, is illustrated in Figure 3.4. Initially, the sensor is at an Initial discovery state (D) during which it discovers its neighborhood, then a CRA is executed to identify the first state transition to either the active state (A) or the sleep state (S). Thereafter, it swings continually between the two states until the depletion of its energy.

Note that EACPs-RS consider only the area coverage type because the redundancy control strategy (Section 3.3.1), determine the sensors' redundancy according on the amount of overlap between neighbors in a regular area (a region). To understand the working of EACPs-RS, we explain a few of them in the following section.

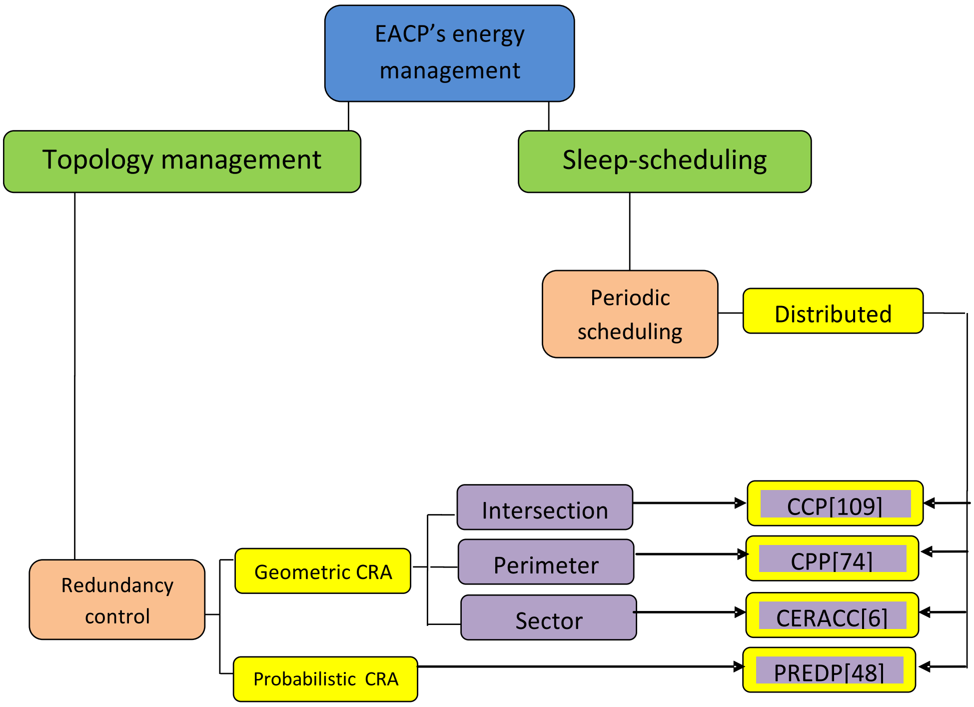


Figure 3.3: EACPs-RS examples.

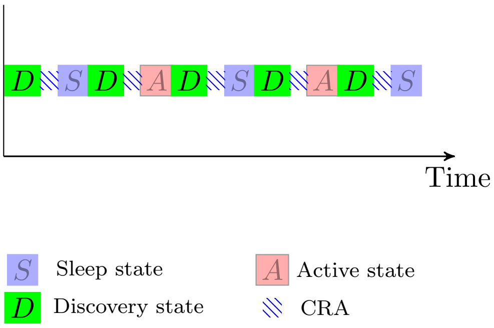


Figure 3.4: EACPs-RS's behavior.

3.4.1 EACPs-RS examples

We present in this section, four EACPs-RS that share the same scheduling mechanism (periodic distributed) but use different CRAs (geometric or probabilistic). We present for each of the four protocols its corresponding CRA and scheduling. The four protocols are:

1. Probabilistic Redundancy Protocol (PREDP)[48].
2. Coverage Connectivity Protocol (CCP)[111].
3. Coverage Preserving Protocol (CPP)[75].
4. Centralized Randomized k-Coverage Proctol($CERACC_k$) [6].

Probabilistic Redundancy Protocol (PREDP) [48]

A new probabilistic approach is adopted in [51, 48] to derive the expected redundancy degree in an heterogeneous WSN. The expected redundancy degree can be considered as the probability for a sensor to be redundant.

First, the authors define a point X within a sensing disk of a sensor s_i, It is a distance of x from the centre of s_i, then estimate the probability $p_{ij}(x)$ for the point X to be covered by a neighbour s_j, $p_{ij}(x)$ is equal to:

$$p_{ij}(x) = \frac{\| A(X, r_j) \cap A(s_i, R_i) \cap A(s_i, R_j)) \|}{\| A(s_i, min(R_i, R_j)) \|} \tag{3.1}$$

where:

- A(α, β) is the surface area centred at the point α, with a radius β
- X is a point in A(s_i, S_i) at a distance x from s_i.
- r_i and r_j are the sensing ranges of the sensors s_i and s_j, respectively.
- R_i and R_j are the communication ranges of the sensors s_i and s_j, respectively.

Several cases are discussed in [48] according to the different equation parameter values. The scheduling algorithm considers three states: ACTIVE, WAIT and SLEEP. It uses two messages HELLO and SLEEP to disseminate information. Initially, the sensor is in ACTIVE state at the beginning of a round and broadcasts a HELLO message. Sensors that receive this message store information about their neighbors, then check their redundancy according to a redundancy table which contains the list of neighbors with their corresponding redundancy probabilities.

Coverage Connectivity Protocol (CCP)[111]

In [111], the authors introduced CCP (Coverage Connectivity Protocol), one of the most known coverage protocols. The main contributions of the CCP protocol is its maintenance of both sensing coverage and connectivity , using a precise relationship. Indeed, the authors prove in [111] that the coverage implies the connectivity if the communication range is greater than or equal to twice sensing range ($R >= 2r$). These theorem has been taken into account in several works to justify the connectivity achievement (e.g, [75, 26]). CCP is also able to dynamically configure both coverage and connectivity degrees and exploits the intersection point strategy to check redundancy. In fact, a node is redundant in CCP if all intersection points inside its sensing disk, are at least k-covered by active neighbors. To conserve their energy, the activity of nodes in CCP is alternated using a load balancing scheduling algorithm. CCP considers five states, namely: LISTEN, ACTIVE, SLEEP, WITHDRAW and JOIN. All

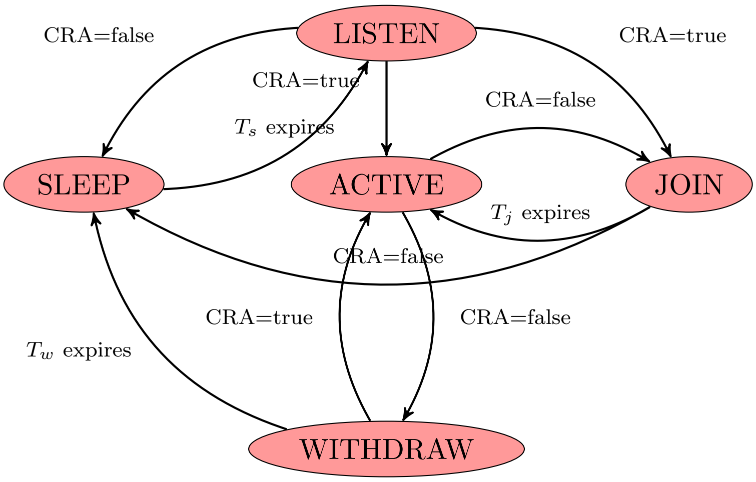


Figure 3.5: The CCP scheduling.

nodes are initially active and when an area exceeds the coverage requirement, due to high density, some nodes become redundant and switch to sleep mode.

The scheduling rules used in CCP are shown in Figure 3.5 and described as follows:

- In SLEEP state. When the sleep timer T_s expires, a node turns on the radio, starts a listen timer T_l, and enters the LISTEN state,
- In LISTEN state. When one of the messages (HELLO, WITHDRAW, or JOIN message) is received, a node evaluates its redundancy. If it is eligible (CRA=true), it starts a join timer T_j and enters the JOIN state. Otherwise, it sets the sleep timer T_s and returns to the SLEEP state.
- In JOIN state. If a node becomes redundant before the expiration of T_j, it cancels T_j, starts T_s, and returns to the SLEEP state. If T_j expires, it broadcasts a JOIN message and enters the ACTIVE state.
- In ACTIVE state. If it is redundant, it starts a withdraw timer T_w and enters the WITHDRAW state.
- In WITHDRAW. If a node becomes eligible before the T_w expires, it cancels the T_w and returns to the ACTIVE state. If T_w expires, it broadcasts a WITHDRAW message, starts a sleep timer T_s, and enters the SLEEP mode.

Coverage Preserving Protocol (CPP)[75]

Like CCP, CPP supports configurable coverage degree for various applications and employs the same rule to ensure the network connectivity ($R >= 2r$). However, the CPP's CRA, called *(ERPC)*, is based only on the knowledge of sensing disk perimeters. In fact, to decide about the redundancy of a sensor s_i, ERPC checks the coverage degree

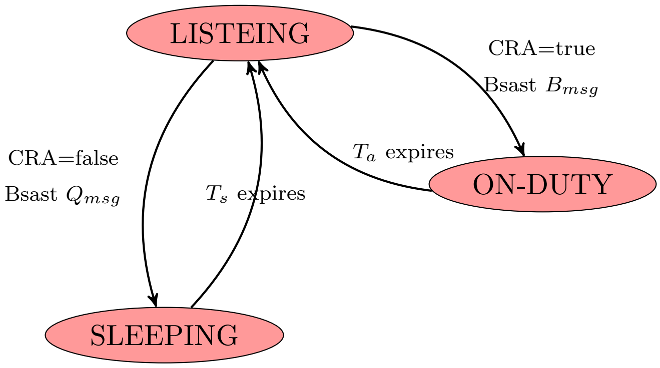


Figure 3.6: The CPP scheduling (SCPP).

of each neighbors' perimeter within the s_i's sensing disk. Let $N(i)$ be the neighbor list of s_i, the ERPC rules are as follows [75]:

1. For a node s_j ($j \in N(i)$), let d(i,j) be the distance between s_i and s_j. The length of the s_j's segment covered by s_i, is calculated.

2. For each s_j s neighbor, s_m, ($m \neq i$), the s_j s arc segment covered by s_m, is calculated.

3. All points generated by the last step are added to a list, then the coverage degree of each arc segment is calculated.

4. Repeat the previous step for each s_m.

5. Repeat the four previous steps for each s_j.

   If there exists a node, whose arc segment covered by s_i, is less than required coverage degree k then s_i is considered not redundant.

Despite the complexity of ERCP, CPP adopts a simple scheduling denoted (SCPP). It considers only three states, namely: *Sleeping*, *On-duty* and *Listening*. Each node evaluates its eligibility, broadcasts either Q_{msg} *(Quit Message)* to enter *Sleep* state if redundant, or B_{msg} (Beacon Message) to enter *On-duty* state, if not redundant. The CPP's scheduling is illustrated in Figure 3.6.

Centralized Randomized k-Coverage Protocol ($CERACC_k$) [6]

In [6], Ammari *et al* propose the Centralized Randomized k-Coverage Protocol ($CERACC_k$) which uses the *Reuleaux Triangle (RT)* geometric shape to determine the sensor redundancy. RT is a shape formed from the intersection of three circular disks, each having its center on the boundary of the two others as depicted in Figure 3.7

The scheduling proposed in [6] is similar to SCPP. It considers three states: *Ready*, *Waiting* and *Running*. A sensor starts listing to awakening message. From *Ready*

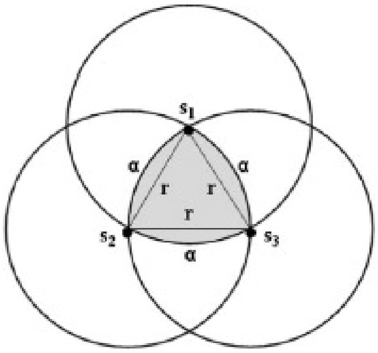


Figure 3.7: Reuleaux Triangle formed by the intersection of three sensors s_1, s_2 and s_3.

state, it enters *Running* state where it communicates with other sensors and senses the environment or switch to *Waiting* when the ready timer expires. It swings between *Running* and *Waiting* states until the energy expiration.

3.5 Notes

As described in this chapter, several EACPs have been developed to extend the network lifetime by managing the coverage energy. These protocols generally share the same objectives which are coverage, connectivity, energy saving and optionally others like fault tolerance. All aforementioned EACPs aim to construct complete or partial coverage with in distributed or centralized manner. Table 3.2 summarizes some EACPs' characteristics.

Table 3.2: Comparative study of EACPs .

EACPs	**EACPs-RS or not**	**CRA principle**	**CRA Complexity**	**Scheduling type**	**Drawbacks**
CCP [111]	Yes	Geometric (Intersection) (Intersection)	$O(n^3)$	Periodic Distributed	- High CRA computation time. - Frequent CRA executions.
CAR [17]	No	-	-	Periodic Centralized (Set-cover)	- Connectivity unsupported
CPP [75]	Yes	Geometric (perimeter)	$O(n^2.log(n))$	Periodic Distributed	- High CRA computation time. - Frequent CRA executions.
CERACC [6]	Yes	Geometric (sector)	$p.O(n)$	Periodic Centralized	- Expensive cluster maintenance.

Table 3.2: Comparative study of EACPs .

EACPs	**EACPs-RS or not**	**CRA principle**	**CRA Complexity**	**Scheduling type**	**Drawbacks**
PREDP [51]	Yes	Probabilistic	-	Periodic Distributed	- Connectivity unsupported.
MoBibar [101]	No	-	-	Periodic Centralized (Set-cover)	- Many iterative checks.

In summary we can deduce that even most EACPs-RS were initially designed to conserve the coverage energy. However, the energy of these protocols is otherwise wasted for many reasons. In fact, the switch between the scheduling states is frequent and dynamic. This situation may considerably increase the communication overhead, as the sensor should continually notify its neighbors of its new state. Moreover, an extra computation energy may be lost due to frequent CRA executions which is imperatively executed at the beginning of each round and after each notification to be aware of the next scheduling transition. In addition, the complexity of most EACP-RS' CRAs is very high even for 1-coverage as shown in Table 3.2.

3.6 Conclusion

In this chapter, we conducted a comprehensive study on energy-aware coverage protocols (EACPs), especially those based on periodic scheduling and redundancy control (EACPs-RS). Beside their heterogeneity, either in their assumptions or objectives, most of EACPs-RS share two main drawbacks: the frequent CRA and transitions repetitions during the scheduling and the high CRA complexity time during the redundancy control. In the next chapter, we suggest two improvements to overcome the two previous drawbacks.

Chapter 4

SPEC: Energy-Efficient Coverage Protocol Based on Stable and Predictive Scheduling In Wireless Sensor Networks

4.1 Introduction

To preserve energy and extend the network lifetime while achieving coverage, most energy-efficient coverage solutions first detect redundant sensors through *eligibility algorithms* also known as *coverage redundancy algorithms (CRAs)*, then schedule their activity through *scheduling techniques*. Note that most existing scheduling techniques adopt a periodic approach; that is, they alternate the redundant nodes' activity to smoothly reduce their energy consumption.

However, the frequent and dynamic alternation between active and sleep modes [55, 104, 131, 129, 53, 66] leads to two major shortcomings:

1. An extra energy consumption may be incurred due to repeated transitions, as the switch energy is not always negligible.
2. Further computation and communication costs may also be incurred, as the sensor should repetitively execute the eligibility algorithm, then broadcast a notification about its new state after each transition.

In this chapter, we propose a coverage protocol called Stable and Predictive Energy-aware Coverage Scheduling (SPEC). SPEC reduces the wasted switch energy by adopting a *one-way*, or a*stable* scheduling evolution when moving from one state to another. Indeed, once active, the sensor stays in this state until exhaustion of its energy reserves, which eliminates many transitions between the active and sleep states. Moreover, the computation energy in SPEC is considerably reduced as the sensor does not execute the eligibility algorithm while being active.

Shorter versions of the stable and predictive scheduling contribution were stated in [26, 27]. In this chapter, more details, deeper simulation scenarios and performance evaluation analysis are provided with respect to [26, 27]. The main contributions are as follows:

1. A one-way scheduling behavior is proposed to reduce the switch energy loss. Indeed, many transitions are eliminated thanks to the continuous sensor activation.
2. A new wakeup strategy is proposed to adjust the sleep timer according to the active sensors' energies. Hence, the new wakeup strategy prevents the creation of uncovered areas when most sensors are asleep.
3. A prediction procedure is proposed to reduce the computation energy loss. In fact, it prevents the run of unnecessary eligibility executions.

The remainder of this chapter is organized as follows: Section 4.2 reviews the motivation of the work. Section 4.3 presents the scheduling algorithm (SPEC). Section 4.4 and Section 4.5 introduce the prediction procedure and the complexity analysis, respectively. Section 4.6 provides simulation results. Finally, Section 4.7 concludes the chapter.

4.2 Motivation

Most scheduling techniques in k-coverage configurations, are periodic [115]. A periodic scheduling relies on a load balancing strategy to schedule nodes and allows them to be periodically active. In fact, the common behavior, in most periodic scheduling schemes, is as illustrated in Figure 4.1: Initially, the sensor is at an Initial state (D) during which it discovers its neighborhood, then an eligibility algorithm (CRA) is executed to identify the first state transition to either the active state (A) or the sleep state (S). Thereafter, it swings continually between the two states until the depletion of its energy.

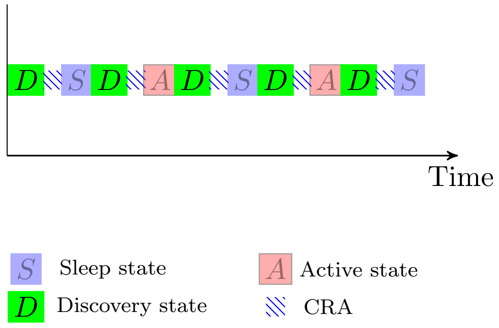


Figure 4.1: Frequent state transitions and eligibility checks in common periodic scheduling schemes.

Table 4.1: Typical values of energy costs in different modes for IEEE 802.15.4 [134]

Sensor mote	Transmit energy (mA)	Receive energy (mA)	Idle energy (mA)	Sleep energy (mA)
CC2480	27	27	12	0.5
CC2420	17.4	18.8	20	1

Table 4.2: Transition energy and delay for IEEE 802.15.4 (CC2420 sensor mote) [13] [90]

Transition	Consumed energy	Duration
Idle→Transmit	9.93 μJ	194 μs
Idle→Receive	6.63 μJ	194 μs
Sleep→Idle	691 pJ	970 μJ

However, the switch between states in most scheduling algorithms is frequent and dynamic [106, 98, 6, 109, 132]. A sensor may uselessly perform a sequence of switches to finally find out that it should simply remain in its initial state. This situation may considerably increase the communication overhead as the sensor should continually notify its neighbors of its new state. Furthermore, switching a radio on and off so often may also result in more energy consumption than leaving the transceiver unit in Idle mode.

Table 4.1 reports some typical values of energy costs for the IEEE 802.15.4 interfaces [134]. The energy dissipated by all possible transitions for a CC2420 card implementing IEEE 802.15.4, are presented in Table 4.2 [13][90].

Besides the extra switch energy, the sensor may waste, during a periodic scheduling, further energy due to frequent CRA executions. In fact, the CRA is imperatively executed by a sensor at the beginning of each round to decide the next scheduling transition. It is also re-executed after each notification reception to check whether the sensor stays active or not (See Figure 4.2).

Coverage and energy consumption issues have been extensively investigated in the literature [41, 32, 50, 126, 60, 78, 129, 85, 52] but, to the best of our knowledge, no work has tackled the impact of frequent switching and eligibility algorithm execution, produced during scheduling iterations, on the coverage energy consumption. Indeed, this chapter addresses this issue.

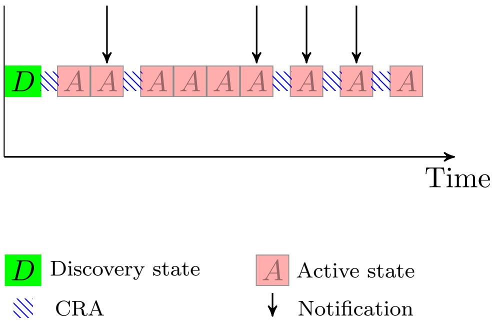


Figure 4.2: Frequent CRA checks after notifications.

4.3 SPEC: Stable and Predictive Energy-Efficient Scheduling Coverage Scheme

Consider a set of sensor, $S = \{s_1, s_2, s_3, ..., s_n\}$, where each node s_i is located at a known coordinate (x_i, y_i) in a region of interest A. A sensor s_i is modeled as a disk of radius r including its boundary. All nodes have the same radius. Let $\delta(s_i, s_j)$ be the Euclidean distance between nodes s_i and s_j.

SPEC is a fully distributed scheduling strategy. Sensor nodes involved in the coverage process are configured to operate in four different states, namely: *Discovery*, *Active*, *Sleep* and *Exhausted*.

In the *Discovery* state, the sensor sends and receives messages to discover its neighborhood, whereas in the *Active* state, it actively senses the environment and communicates with other nodes. In the *Sleep* state, the sensor is turned off. Finally, in the *Exhausted* state, the node is about to run out of energy. The notations used by SPEC are summarized in Table 4.3.

Table 4.3: SPEC notations.

Notation	**When it is used**
Activity Message (AM)	When the sensor become active
Discovery Message (DM)	To prompt neighbors to construct their neighborhood tables
Discovery timer ($T_{Discovery}$)	To broadcast and receive DMs.
Random Timer (T_{rand})	To wait before computing eligibility.
Sleep timer (T_{sleep})	To sleep before beginning a new round
$T_{Ready\_To\_Be\_Active}$	To wait before activating
Activity timer ($T_{activity}$)	To spend in the active state
Activity threshold timer ($T_{act\_threshold}$)	To enter the exhausted state

The stable SPEC scheduling adopts a one-way evolution when moving from one state to another. That is, the sensor stays active until exhaustion and there is no direct backtracking to the sleep state after activation (Figure 4.3).

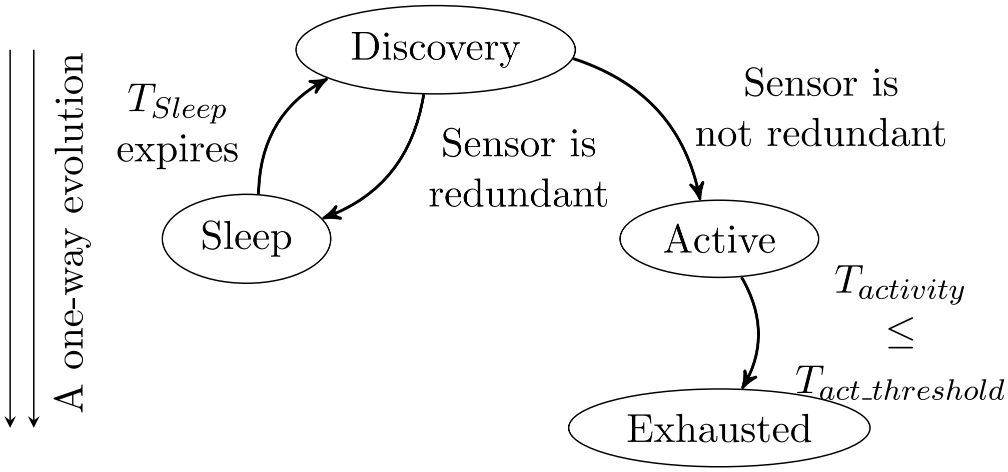


Figure 4.3: SPEC diagram transition with a one-way evolution.

Initially, all nodes are in the *Discovery* state; a discovery timer $T_{Discovery}$ is set up and a discovery message DM is broadcast to prompt neighbors to construct their neighboring tables. The DM contains the node ID, its residual energy, and its current location. After receiving its neighbors' DMs, each node runs the first eligibility algorithm execution. However, blind areas (or uncovered areas) may occur when nodes execute simultaneously the eligibility algorithm. To avoid the appearance of such a problem, SPEC adopts a back-off scheme as in [104]: each node waits for a random delay T_{rand} before executing CRA and disseminating the status. Indeed, the neighbor with a longer T_{rand} will evaluate its eligibility without taking redundant nodes into account.

To estimate the amount of overlap, eligibility algorithms in the literature are based either on geometric implementation methods [111, 29, 30], or on analytical ones [15, 49, 102, 67])[1]. We assume, in this chapter, that the eligibility algorithm is a black box or a function (based on geometric or analytical methods) that returns the sensor's eligibility status, whether redundant or not.

- **Case 1: The node is redundant;** Since its area is completely covered by neighbors, the awakening of such a node is not urgent. Thus, the node enters the *Sleep* mode and sets a sleep timer T_{sleep}. Note that the value of T_{sleep} must be carefully chosen since the sleep timer may influence not only the energy consumption but the quality of the monitoring task as well [14]. For instance, a shorter sleep timer leads to quick wake-ups and the nodes may therefore not be able to conserve enough energy. Meanwhile, a longer timer favors energy conservation but may cause coverage holes if, over time, some active neighbors run out of energy or die. The appropriate sleep timer is defined via the wakeup strategy detailed in Section

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[1] Geometric methods involve area calculation to quantify the amount of overlapping between nodes, while the analytical ones estimate the probability that the sensing disk of a given node is completely covered by its neighbors' sensing disks.

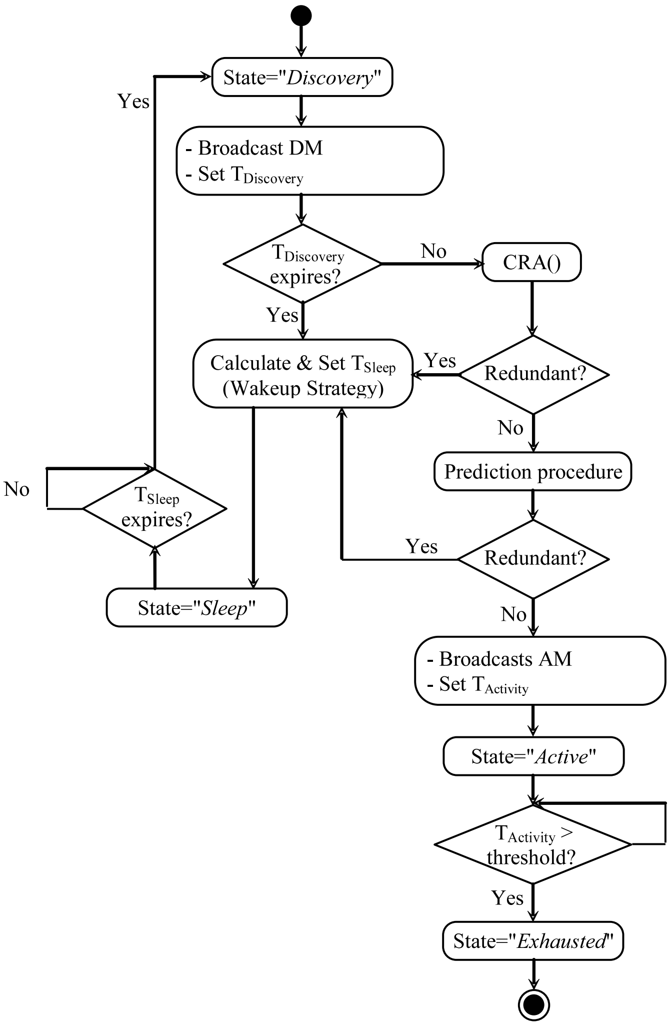

Figure 4.4: SPEC scheduling strategy.

4.3.1.

- **Case 2: the node is not redundant;** In this case the sensing disk of such a node is partially covered. According to the stable scheduling strategy adopted by SPEC, it will likely go into the *Active* state and remain there during its activity timer $T_{activity}$. When it reaches the activity threshold timer $T_{act\_threshold}$, it enters the Exhausted state[2].

  Due to the irreversibly of the activation, SPEC adopts a new strategy to delay, as much as possible, the activation of eligible nodes. The activation delay is detailed in Section 4.3.2.

Figure 4.4 describes the entire SPEC scheduling process.

---

[2] Recall that the *Exhausted* state is an active state where the node is about to run out of energy.

4.3.1 SPEC Wake Up Strategy: How Long May a Sensor Remain in The Sleep State?

Several existing scheduling solutions propose methods for turning off as many nodes as possible [71, 75], but few have focused on the wakeup strategy [14, 88]. Although it is important to decide when a node should go into sleep mode, it is also necessary to determine when sleeping nodes should wake up and take over the exhausted node's area in order to avoid coverage holes. Indeed, if a node dies between two rounds, events occurring within its area may not be detected by active neighbor nodes and sleeping nodes will not be able to monitor the uncovered area before the next round starts [14]. To overcome this shortcoming, some schemes, like [14], propose to notify the sleeping nodes about the exhaustion of their active neighbors by sending wakeup messages. However, such a solution induces high communication overhead and requires an additional communication channel that keeps receiving wakeup messages even if nodes are in sleep mode. To address the aforementioned problems, we devise a simple yet efficient wakeup strategy that adjusts the sleep timer, T_{sleep}, according to the remaining energy of the active neighbors. Thus, a sleeping node should wake up before the exhaustion of its lowest-energy active neighbor. In doing so, the proposed wake up strategy prevents blind points with lower cost. Therefore, a node does not need too many message exchanges, as it is aware of its neighbors' status and their remaining energies just after its CRA execution step as already shown in Figure 4.4.

Let $T_R(s)$ denote the remaining lifetime of a sensor s according to its available energy. Let S_a be the set of active neighbors. The sleep timer T_{sleep} is given by:

$$T_{sleep} = \min_{\forall s \in S_a} T_R(s). \tag{4.1}$$

4.3.2 SPEC Activation Delay Strategy

Recall that in SPEC, nodes that transit to the active state will remain in this state until their exhaustion. Obviously, this may lead to high energy consumption. To address this issue, SPEC adopts an activation strategy that delays as long as possible the irreversible activation of eligible nodes. To this end, a sensor selected by CRA algorithm as eligible for activation will start a timer $T_{Ready\_To\_Be\_Active}$ and wait for receiving AM messages from active neighbors that can completely cover its blind area. Thus, an eligible node goes to the active state only if no active neighbors can fill its uncovered area. We assume that $T_{Ready\_To\_Be\_Active}$ time is sufficient enough to receive all AM messages from all sensor's active neighbors.

Algorithm 1 describes the activation delay strategy: During time interval $T_{Ready\_To\_Be\_Active}$ and at each reception of AM from a neighbor, the sensor re-executes the CRA algorithm to check whether it is still eligible for activation (lines 1-3). The sensor becomes ineligible when it receives an AM from a neighbor that can cover its uncovered area.

Algorithm 1 Activation_Delay()

```
1:  while $T_{Ready\_To\_Be\_Active}$ not expired do
2:    if $Rcvmsg \rightarrow type = AM$ then
3:      $CRA()$;
4:      if $Is\_Redundant$ then
5:        $Cancel\ (T_{Ready\_To\_Be\_Active})$;
6:        Goto Sleep State;
7:        Break;
8:      end if
9:    end if
10: end while
11: if $T_{Ready\_To\_Be\_Active}$ expired then
12:   $CRA()$;
13:   BroadcastAM;
14:   Goto Active State;
15: end if=0
```

In this case, the sensor cancels $T_{Ready\_To\_Be\_Active}$ and goes into the sleep state (lines 4-9). However, if $T_{Ready\_To\_Be\_Active}$ expires without receiving any AM satisfying the ineligibility condition, the node enters the active state and broadcasts an AM to inform about its activity (lines 11-14).

4.3.3 Discussion

SPEC is a fully distributed algorithm where each sensor collaborates with its neighbors to decide upon the appropriate state. As a result, all ineligible nodes transit to the sleep state, while just a subset of eligible nodes will be active. To further increase the number of sleeping nodes, $T_{Ready\_To\_Be\_Active}$ timer can be adjusted according to residual energy. The higher the node's remaining energy is, the shorter its $T_{Ready\_To\_Be\_Active}$ timer will be. Consequently, prioritizing the activation of nodes with the highest residual energy will allow longer activation time and hence avoid the wake-up of many other nodes, especially those with low remaining energy. Nevertheless, the activation strategy in SPEC induces a high computation cost due to the execution of CRA upon the reception of each AM during the $T_{Ready\_To\_Be\_Active}$ time interval. Indeed, CRA is performed $(m+1)$ times: one execution at the beginning of the first round and m executions after receiving each of the m AM messages. Note that $m \leq n$, where m is the number of AM notifications and n is the number of neighbors. One possible solution to reduce the execution of CRA is to set up a prediction strategy that decides whether CRA should immediately be executed or not.

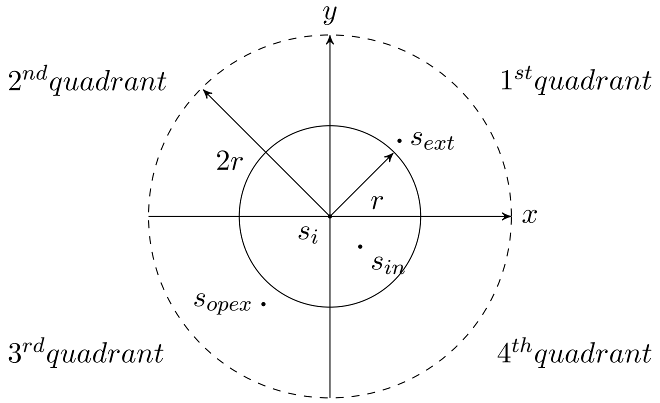

Figure 4.5: An example illustrating the sender types of AM received by node s_i: Internal neighbor (s_{in}), external neighbor (s_{ext}), and opposite external neighbor (s_{opex}).

4.4 Prediction Procedure

The prediction procedure checks whether to run the CRA immediately after an AM reception based on the AM's sender type. As illustrated in Figure 4.5, the sender type is either *i) Internal*, located inside s_i's sensing disk, *ii) External*, located between r and $2r$[3], where r is the radius of s_i's sensing disk or *iii) Opposite External*, which is an external sender located at the opposite quadrant of another external sender.

The prediction procedure runs or delays the CRA execution based only on AM's sender type, as explained in the Algorithm 2. During time interval $T_{Ready\_To\_Be\_Active}$, the sensor s_i gathers the AM notifications and checks their senders' type (lines 2 and 3). If the sender is internal, s_i executes the CRA immediately since there is a high probability that it returns the ineligible value and hence s_i sleeps and conserves its energy. However, as the external sender does not share a large overlap with s_i, the CRA execution is postponed. Assuming that the external sender is located in quadrant q ($q = \overline{1,4}$), its location is saved in $Quad\_Queue(q)$ queue (line 14). Then, the prediction procedure checks whether the external sender has an opposite external node by verifying if $Oppos\_Quad\_Queue(q) \neq \emptyset$ (line 15). In this case, s_i runs the eligibility algorithm because it is likely to sleep as s_i' s holes have a high chance to be covered by the two external senders. If $T_{Ready\_To\_Be\_Active}$ expires without receiving any AM notification, s_i runs the CRA once (line 30). The CRA returns *Eligible* in the worst case and so the sensor will be activated. In fact, this procedure can reduce the CRA execution to only two times in the best case. Nevertheless, it is worth to note that the lightweight prediction does not replace the CRA but simply triggers its execution when necessary and therefore reduces the overall scheduling computation complexity.

---

[3] The two nodes do not have overlapping sensing regions if the distance between them is larger than $2r$.

Algorithm 2 Prediction Procedure()

```
while $T_{Ready\_To\_Be\_Active}$ not expired do
  if $Rcvmsg \rightarrow type = AM$ then
    if $\delta(s_i, s_j) \leq r$ then
      $Internal\_sender = True$;
      $CRA()$;
      if $Is\_Redundant$ then
        $Cancel$ ($T_{Ready\_To\_Be\_Active}$);
        $Goto$ $Sleep$ $State$;
        $Break$;
      end if
    else
      if $r < \delta(s_i, s_j) < 2r$ then
        $External\_sender = True$;
        $Insert\_Into\_Quad\_Queue(q)$;
        if $Oppos\_Quad\_Queue(q) \neq \emptyset$; then
          $Opposit\_external\_neighbor = True$;
          $CRA()$;
          if $Is\_Redundant$ then
            $Cancel$ ($T_{Ready\_To\_Be\_Active}$);
            $Goto$ $Sleep$ $State$;
            $Break$;
          end if
          $Break$;
        end if
      end if
    end if
  end if
end while
if $T_{Ready\_To\_Be\_Active}$ expired then
  $CRA()$;
  $BroadcastAM$;
  $Goto$ $Active$ $State$;
end if=0
```

4.5 Complexity Analysis

In this section, the complexity of SPEC is analyzed and compared to two periodic scheduling schemes, namely: CCP [111] and SCPP [75]. The choice of CCP and SCPP is motivated by the fact that CCP is among the first coverage protocols based on sleep scheduling technique and SCPP is a simple one using a minimum number of states. The complexity of the three algorithms is assessed in terms of (i) *time complexity*, which refers to the number of CRA checks, and (ii) *communication complexity*, which represents the number of exchanged messages during the scheduling process.

4.5.1 Time Complexity

CCP considers five states, namely: *Listen*, *Active*, *Sleep*, *Withdraw* and *Join.* The time complexity quantifies the amount of time taken to run all the eligibility executions in the full scheduling. Considering n neighbors, the number of CRA executions in CCP scheduling is as follows [111]:

- $3n$ in *Listen* state after the reception of $Hello_{msg}$, $Join_{msg}$ or $Withdraw_{msg}$.
- $2n$ in *Join* and $2n$ in *Active* state after $Hello_{msg}$ or $Join_{msg}$ reception.
- $2n$ in *Withdraw* state after $Hello_{msg}$ or $Withdraw_{msg}$ reception.

Therefore CRA runs **9n times** per round in CCP.

On the other hand, SCPP considers only three states, with no intermediate state, namely: *Sleeping*, *On-duty* and *Listening.* Each node evaluates its eligibility, broadcasts either Q_{msg} *(Quit Message)* to enter *Sleep* state if redundant, or B_{msg} (Beacon Message) to enter *On-duty* state. Thus, the number of CRA executions in SCPP scheduling is as follows [75]:

- $2n$ in *On-duty* when receiving Q_{msg} or B_{msg}.
- $2n$ in *Listening* when receiving Q_{msg} or B_{msg}.

As a result, the CRA execution in SCPP is **4n times** per round. Meanwhile, SPEC runs CRA **p times, (**$p < n$**)**, for the whole duration of the network's lifetime, as shown in the previous section.

4.5.2 Communication Complexity

Let N be the total number of nodes in the network and n the maximum number of neighbors.

Each CCP active node can visit the *Join* state α times (to send *one* $Join_{msg}$), and *Withdraw* state β times (to send *one* $Withdraw_{msg}$). Moreover, a CCP sleeping node can return to *Listen* state and sends *one* $Hello_{msg}$ γ times. Hence, the total number of exchanged messages in CCP scheduling is $O(N(\alpha + \beta + \gamma))$, where $1 \leq \alpha, \beta, \gamma \leq n$.

On the other hand, the number of exchanged messages in SCPP scheduling is as follows:

- *One* Q_{msg} or B_{msg} in *Listening* state.
- *One* Q_{msg} or B_{msg} in *On-duty* state.

Moreover, an *On-duty* SCPP node can switch to *Listening* state η times and a *Sleeping* SCPP node can do it ω times.

Therefore, the total number of exchanged messages in SCPP scheduling is $O(2N(\eta + \omega))$, where $1 \leq \eta, \omega \leq n$.

In the case of SPEC, a node broadcasts only:

- *One DM* in *Discovery* state.
- *One AM* in *Discovery* state.

Hence, the total number of exchanged messages in SPEC scheduling is $O(2N)$.

4.6 Performance Evaluation

To assess SPEC's performances, simulation experiments are conducted using the network simulator (NS-2). The simulation parameters are listed in Table 5.4. The nodes' sensing range is set to 20 m and the communication range is set to 200 m. The coverage degree is varied between 1 and 11. The number of sensors is varied between 10 and 225, they are uniformly deployed in 100 m x 100 m area. We assume that a node wastes 0.6 J when transiting from one state to another [95] and 0.026 J to execute each instruction of the eligibility algorithm [35, 73, 10]. We assume also that the overall CRA time execution is 5 J.

The performance of SPEC is compared with the performance of two periodic scheduling schemes, namely: CCP [111] and SCPP [75]. Moreover, SPEC is compared to SECWP; a variant of SPEC without the prediction procedure. The reason behind that comparison is to show the energy efficiency of the prediction procedure. To make a fair comparison, all schemes execute the same eligibility algorithm of [111].

The four schemes (i.e., SPEC, SECWP, CCP and SCPP) are evaluated in terms of the following metrics:

- Stability: measured as the average number of transitions carried out along the network lifetime;
- Eligibility frequency: measured as the average CRA checks over the network lifetime;

Table 4.4: SPEC settings.

Notation	**Value**
Space	100 m x 100 m
Nodes	10-225
Coverage degree (k)	1-11
Sensing range (r)	20 m
Communication range (r_t)	200 m
MAC	IEEE 802.11
Initial energy	200 J
Idle Power	0.75 W
Sleep Power	0.025 W
Transmission Power	1.90 W
Reception Power	1.50 W
Switch Energy	0.6 J
Computation Energy	0.026 J

- Energy consumption and the network lifetime when considering both switch and computation energies;

- Average number of active nodes;

- Coverage degree (k): It measured the monitoring quality and whether a region can be covered by at least k active nodes or not;

4.6.1 Stability

The stability of a scheduling algorithm is measured as the average number of transitions between states for the whole duration of the network lifetime:

$$Stability\ (tr/s) = \frac{Number\ of\ transitions}{Network\ lifetime}. \tag{4.2}$$

The average number of transitions per second in the case of SPEC, its variant SECWP, CCP and SCPP is depicted in Table 4.5. The obtained results show that the envisioned scheduling schemes yield fewer transitions compared to CCP and SCPP, thanks to its wake up strategy. Table 4.5 also demonstrates that SPEC reduces the number of transitions by more than 50% compared to SECWP. Indeed, the absence of the prediction procedure constrains a SECWP node to execute the CRA after each AM notification, leading to more transitions between states.

Table 4.5: The average transitions per second ($n = 225$, $r = 20$ m).

Coverage protocol	**Average transitions (tr/s)**
CCP [111]	35.21
SCPP [75]	26.25
SECWP	1.66
SPEC	0.9

Table 4.6: The CRA checks per second ($n = 225$, $r = 20$ m).

Coverage protocol	**Average CRAs (cra/s)**
CCP [111]	12.41
SCPP [75]	8.99
SECWP	0.82
SPEC	0.46

4.6.2 Eligibility frequency

As mentioned above, the eligibility frequency is defined as the average CRA checks carried out by a scheduling scheme during the network lifetime:

$$Eligibility\ frequency(cra/s) = \frac{Number\ of\ CRA\ executions}{network\ Lifetime}. \tag{4.3}$$

Table 4.6 exhibits the superior performance of the proposed scheduling scheme SPEC in terms of the number of CRA checks. The reason behind this is that SPEC takes advantage of the delay activation strategy and the prediction procedure to reduce the number of CRA checks. Furthermore, the prediction procedure allows SPEC to avoid many unnecessary eligibility checks, thereby inducing 50% less CRA executions compared to SECWP.

4.6.3 Energy consumption

It is worth stressing that a sensor consumes energy not only when sending and receiving messages, but even when performing computations and switching between states. Thus, the impact of the computation and state switching power in the overall energy consumption is taken into account in our evaluation; this consumption was neglected in similar works (e.g., [75, 111]).

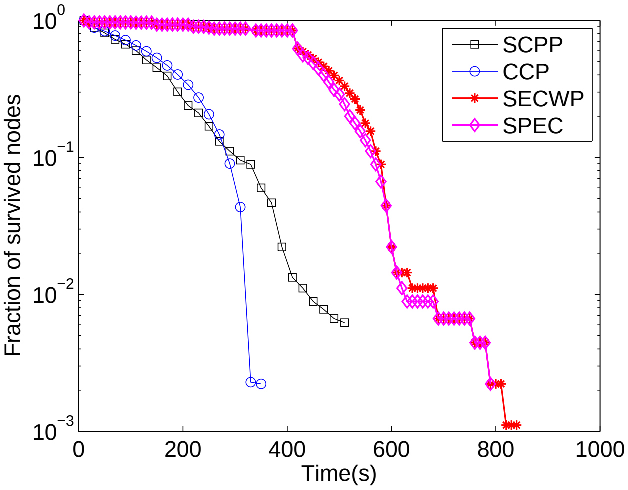

Figure 4.6: Network lifetime (Log scale on y-axis, $n = 225$, $r = 20$ m).

Network Lifetime

We define the network lifetime as the rate of nodes alive (i.e., nodes with positive energy) over the time. It is given by the following equation:

$$Lifetime\_Rate_{(t)} = \frac{N\_nodes_{(E>0)}}{N\_nodes_{(t=0)}}. \tag{4.4}$$

where $N\_nodes_{(E>0)}$ is the number of nodes having a positive energy, and $N\_nodes_{(t=0)}$ is the initial number of nodes.

Figure 4.6 (note the logarithmic scale on the y-axis) clearly shows that nodes run out of energy earlier in periodic schemes (i.e., CCP and SCPP) than in our schemes (i.e., SPEC and SECWP). This can be explained by the high energy consumption induced by state switching, computation and communication in periodic schemes. The figure shows that SECWP extends the network lifetime by 53% and 35% compared to CCP and SCPP, respectively. Furthermore, the prediction procedure allows SPEC to extend the network lifetime by 56% and 38% compared to CCP and SCPP, respectively. Indeed, the last node dies at 850 s when SPEC scheme is applied, while it dies at 800 s, 520 s and 370 s when SECWP, SCPP and CCP schemes are applied, respectively.

Switch energy

The switch energy is the amount of energy spent by nodes on switching between the different states. Figures 4.7 and 4.8 depict the total switch energy consumed by nodes over the network lifetime when CCP, SCPP, SPEC and SECWP schemes are used. Comparing the two figures, it can be noticed that the SPEC and SECWP schemes achieve low switching energy cost compared to CCP and SCPP. The reason behind that is the limited transitions between states recorded in SPEC and SECWP schemes thanks

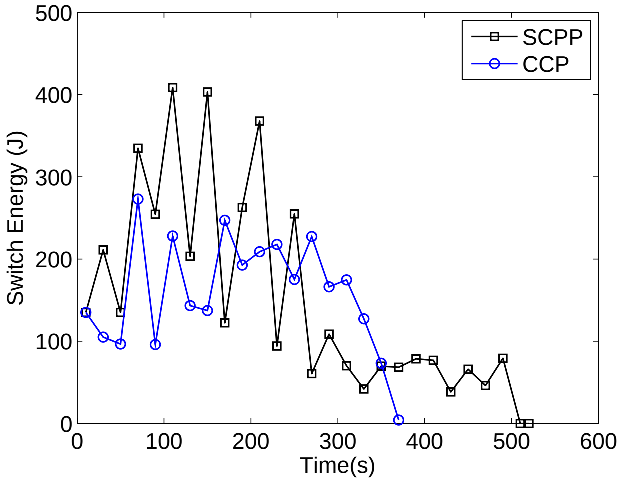

Figure 4.7: CCP and SCPP switch energy vs. time ($n = 225$, $r = 20$ m).

to their delay activation strategy and the prediction procedure. Note also that unlike CCP and SCPP, SPEC and SECWP schemes go through “stable switching-periods” where no transitions are recorded. Those periods are represented on Figure 4.8 by intervals [0 s, 410 s] and [600 s, 800 s] for SECWP and intervals [0 s, 410 s] and [630 s, 850 s] for SPEC. Indeed, a sufficient subset of nodes is initially activated to achieve a full 1-coverage of the area in question. Thus, no transitions between states are made as long as the activated nodes have enough energy to ensure the area coverage, which result in the first stability period. This period ends when active nodes start dying which results in the wake up of sleeping nodes to replace the dead ones. Hence, more transitions between states are generated inducing increased switching energy consumption. The second stability period begins when all nodes become active. This is due to the fact that both schemes SPEC and SECWP adopt a one-way approach when moving from one state to another. Therefore active nodes do not switch to other states until exhaustion. It is worth noting that the second stability period is slightly longer when the SPEC scheme is used thanks to its prediction procedure.

Computation energy

Figures 4.9 and 4.10 depict the computation energy consumed due to the eligibility checks in the four protocols. As can be observed, SECWP and SPEC achieve significantly lower computation energy consumption than the periodic schemes CCP and SCPP. Note also that the graphs of SECWP and SPEC go through two “stable computing-periods” when no CRA are executed. “Stable computing-periods” are recorded during [0 s, 410 s] and [600 s, 800 s] intervals for SECWP, and during [0 s , 410 s] and [630 s, 850 s] intervals for SPEC. No CRA are executed during the first period because the initial coverage is maintained and during the second period because

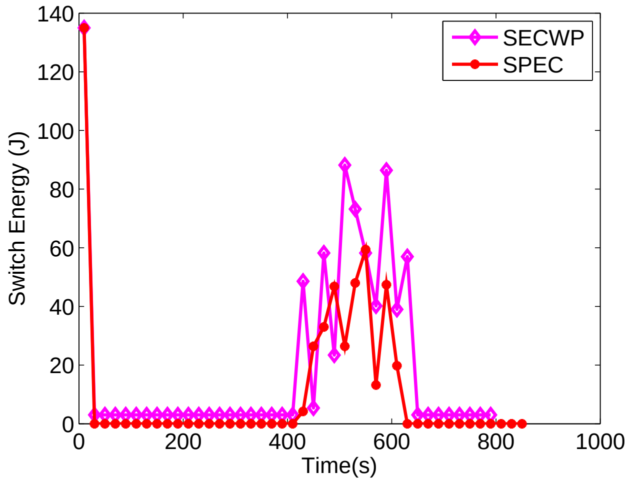

Figure 4.8: SECWP and SPEC switch energy vs. time (n = 225, r = 20 m).

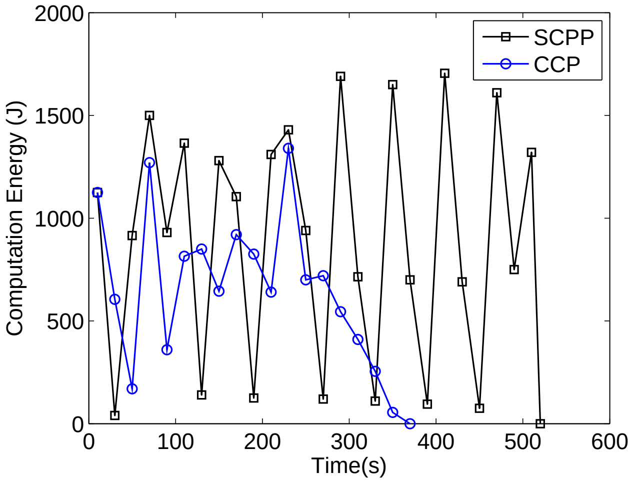

Figure 4.9: CCP ans SCPP computation energy vs time (n = 225, r = 20 m).

all nodes are active.

Overall energy consumption

The overall energy consumption is evaluated when considering computation, sensing (with switching) and communication energies. Figure 4.11 shows that the overall energy consumption is more pronounced in the periodic schemes than it is in our schemes because of their fewer transitions, CRA checks and notifications.

In summary, Table 4.7 recapitulates the key results from previous experiments.

4.6.4 The number of active nodes

Figure 4.13 and Figure 4.14 depict the number of active nodes that cover the 100 m x 100 m region, in periodic and stable schedulings, respectively. Comparing the two

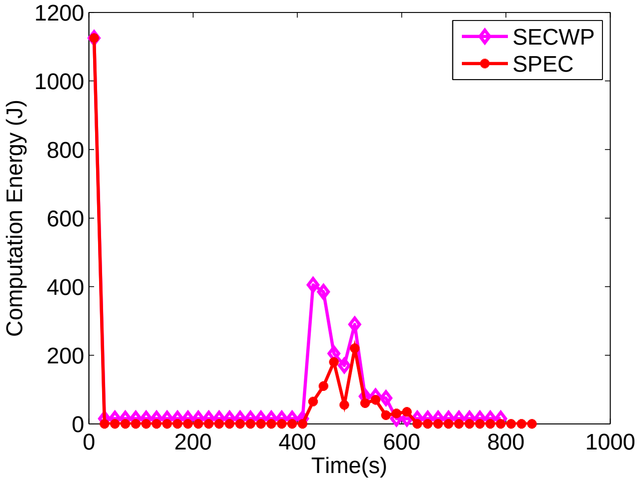

Figure 4.10: SECWP and SPEC computation energy vs time ($n = 225$, $r = 20$ m).

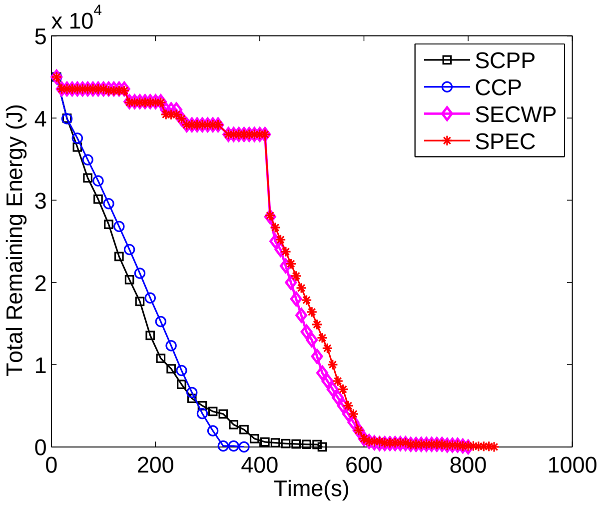

Figure 4.11: Overall energy consumption vs time ($n = 225$, $r = 20$ m).

Table 4.7: Comparison among protocols.

Coverage protcol	Network lifetime (s)	Number of transitions	Average transitions (tr/s)	Transitions energy (J)	Transitions energy percentage	Number of CRAs	Average CRAs (cra/s)	CRAs energy (J)	CRAs energy percentage
CCP [111]	**370**	**13030**	**35.21**	**7818**	**17.37%**	**4592**	**12.41**	**22960**	**51.98%**
SCPP [75]	**520**	**13651**	**26.25**	**8190.6**	**18.2%**	**4679**	**8.99**	**23395**	**51.02%**
SECWP	**800**	**1328**	**1.66**	**796.8**	**1.77%**	**656**	**0.82**	**3280**	**7.28%**
SPEC	**850**	**766**	**0.9**	**459.6**	**1.02%**	**395**	**0.46**	**1975**	**4.38%**

figures, it can be noticed that, initially, the four protocols activate the same number of nodes (20 nodes) to cover this region as they use the same eligibility algorithm. Theoretically, 18 active nodes are sufficient to completely cover it (see Figure 4.12), hence, the four protocols can initially cover it by almost the same number of active nodes. Figure 4.13 shows that once the initial coverage is ensured by 20 active nodes in periodic schedulings, this number increases quickly until reaching 130 in CCP and 90 in SCPP, the other nodes have died. The reason behind that is to fill holes generated by the rapid depletion of nodes. Indeed, nodes die more quickly in both CCP and SCPP because transitions and CRA checks are frequent compared to our scheduling.

Simulation results in Figure 4.14 show that the initial coverage can be maintained in our scheduling through the first stable period ([0 s, 410 s]); the number of active nodes decreases in SPEC and SECWP after the 410 s when some of them become exhausted[4]. Sleeping nodes wake up to replace them. The number of exhausted nodes increases during [410 s, 600 s] until reaching 220 exhausted nodes in SECWP and during [410 s, 630 s] until reaching 200 exhausted nodes in SPEC. This number decreases slowly after 690 s in SECWP and 700 s in SPEC because of the gradual death of nodes. Note that both the gradual activation and the gradual death is slower in our scheduling than in periodic ones. The sensor in this case merely ensures the monitoring task with the lowest possible energy. By doing so, active nodes are able to monitor the region for long periods.

4.6.5 Coverage degree *(k)*

We evaluate in this scenario, the coverage degree (k) given by the following equation [5] :

$$k = \left\lfloor \frac{N\_nodes_{(state=Active)}}{N\_nodes_{(state=Active,\ t=0)}} \right\rfloor. \tag{4.5}$$

where $N\_nodes_{(state=active)}$ is the number of sensors in the active states while $N\_nodes_{(state=active,t=0)}$ is the number of active nodes at t=0. Figure 4.15 shows that

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[4] Exhausted nodes still sense until their death.

[5] $\lfloor\rfloor$ is the integer part of the division.

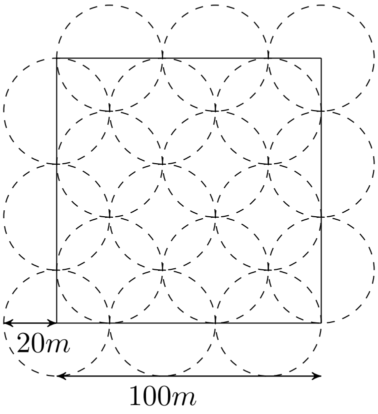


Figure 4.12: Complete 1-coverage using 18 nodes in 100 m x 100 m region, r= 20 m.

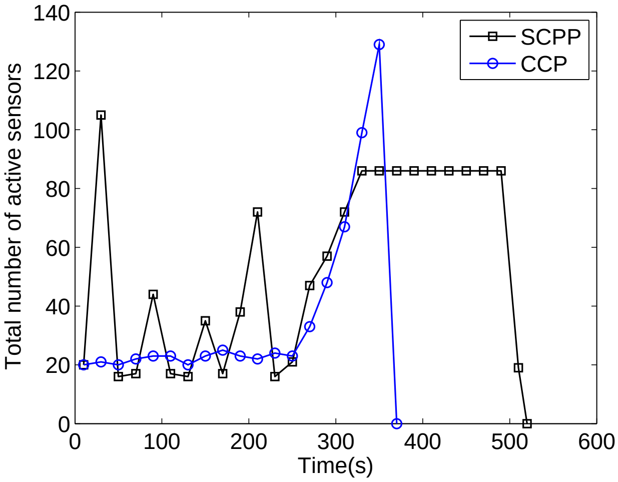


Figure 4.13: Total number of active nodes In CCP and SCPP vs time (n = 225, r = 20 m).

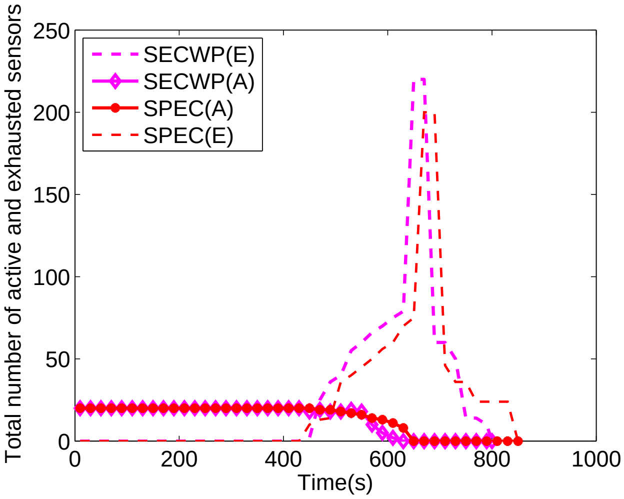


Figure 4.14: Total number of active (A) and exhausted (E) nodes in SECWP and SPEC vs time (n = 225, r = 20 m).

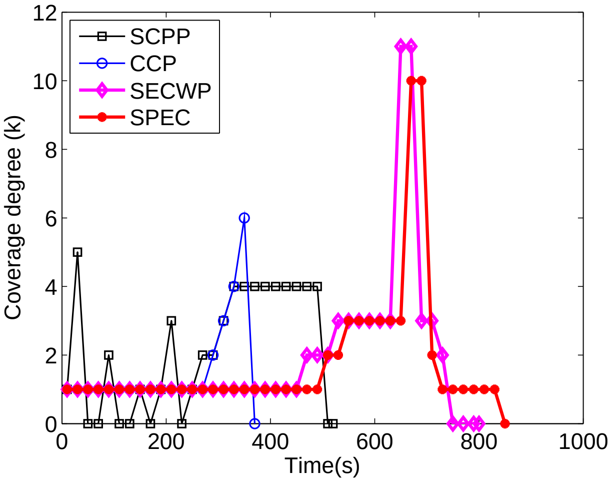


Figure 4.15: Coverage degree in SCPP, CCP, SECWP and SPEC vs. time ($n = 225$, $r = 20$ m).

the coverage degree swiftly increases in CCP and SCPP as a large number of sensors should be activated to fill holes caused by the quick nodes death, hence high coverage degree can be reached but only for short periods (k=4 at t=330 s, k=6 at t=360 s) in CCP, and (k=3 at t=200 s, k=4 during [360 s, 520 s]) in SCPP. Conversely, Figure 5.13 shows also that the coverage degree increases to reach high levels and for long periods (k=3 during [550 s, 650 s], k=10 during [690 s, 700 s]) in SPEC, and (k=3 during [540 s, 640 s], k=11 during [680 s, 690 s]) in SECWP. This is due to the fact that active nodes in our scheduling ensure coverage without executing any eligibility check or transitions, hence they can achieve high coverage degree for longer periods.

4.7 Conclusion

In this chapter we investigated the reduction of the energy consumption during the coverage scheduling by taking into account both, switch and computation energies. Those two aspects have been neglected so far in most scheduling studies. For this purpose, we proposed a Stable and Predictive Energy-Efficient Coverage Scheduling (SPEC) that softens the wasted scheduling energy by evolving a one-way evolution to avoid needless transitions and by predicting the execution of the eligibility algorithm, thereafter. SPEC has several advantages: it is (i) distributed, (ii) feasible for dynamic topologies, and (iii) flexible to any coverage redundancy algorithm. Experimental results show that the scheduling behavior as well as the prediction procedure, show better performance than the standard periodic scheduling regarding energy consumption, k-coverage preservation and the whole network lifetime.

Chapter 5

SRA-SPEC: Lightweight k-coverage Protocol Based on Low-Cost Eligibility and Stable-Predictive Scheduling in WSNs

5.1 Introduction

The main goal of k-coverage protocols is to ensure that each point in the surveillance area is within the sensing range of at least k sensors. Applications requiring a high coverage degree k, ($k > 1$) occur when stronger monitoring is needed. Indeed, the high coverage degree makes the monitoring quality more accurate in many applications (like in intrusion detection [120], data gathering [77, 21] and object tracking [74, 97] applications). Nevertheless, most k-coverage protocols need to activate a great number of redundant sensors, especially when k is high.

To conserve the network energy during coverage, CRAs are executed to determine redundant sensors. Scheduling algorithm are subsequently run to plan the sensors' activity such as the coverage of the entire region still maintained.

We distinguish two CRAs classes, centralized and distributed. The former needs a global view of the FoI, and intensive calculation within a calculation center (a sink). The latter is more energy efficient than the former, but needs the knowledge of all concave and convex shared subregions of the FoI , which is a highly computation intensive task for a sensor.

In this chapter, we propose a new geometric model able to easily resolve the k-coverage problem. It adopts a lightweight distributed CRA to determine redundant nodes. It is denoted *SRA (Sector Redundancy Determination Algorithm)*. SRA accurately determine redundant nodes, whatever the coverage degree needed by the application. Assuming that each sensing disk is logically divided into i sectors, we prove that a sensor is redundant, if all its sectors are covered by neighbors located in some subregions of the sensing disk, denoted *Flower Areas (FAs).* Two enhancements of SRA are also proposed, *SRA-Rot (SRA with Rotation)* and *SRA-Rot-*k_{lmax} *(SRA with Rotation and Local Maximum Coverage Degree)*, respectively. The former explores all possible Flower Areas within the sensing disk, which gives more accuracy to the redundancy determination process. The later, returns an additional information, compared to SRA and SRA-Rot, which is the local maximum coverage degree k_{lmax} provided by each sensor of the FoI. The knowledge of k_{lmax} serves to smoothly derive the coverage degree of the entire FoI. We prove that the time complexity of the three protocols is only $O(n)$, whatever the coverage degree k. Moreover, we propose to join the stable-predictive scheduling SPEC [28] to SRA (or its successor algorithms), to decrease the energy consumption of the entire SRA-SPEC k-coverage protocol. This later maintains both the k-coverage and connectivity of the FoI.

Partial versions of this work were stated in [25, 29, 26, 30, 27] and in [28]. More details, deeper analysis and simulation scenarios are provided in the current chapter.

The remainder of this chapter is organized as follows: Section 5.2 gives the motivation of the work. Section 5.3 presents the new k-coverage model. Section 5.4, Section 5.5 and Section 5.6 describe the three proposed CRAs; SRA, SRA-Rot and SRA-Rot-k_{lmax}, respectively. Section 5.7 presents SRA-SPEC, the new k-coverage protocol. Section 5.8 provides an analysis of simulation results. Finally, Section 5.9 concludes the chapter.

5.2 Motivation

Ensuring k-coverage for a FoI, is checking whether each of its point is covered by at least k sensors. As it can be seen in Figure 5.1, the sensing disk parts of all sensors are covered by either one, two or three sensors. The coverage degree k is the minimum among these numbers (i.e. $k = 1$). The numbers in Figure 5.1 represents the coverage degree of some FoI's subregions. The entire FoI is 1-cover. .

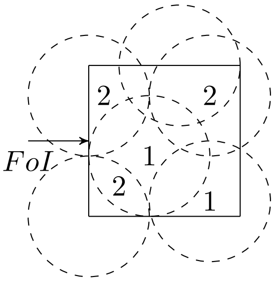


Figure 5.1: The FoI is 1-cover

Redundant sensors, in a k-cover region, are nodes whose disks are completely covered by other neighbors' disk. When the network is dense, as in WSNs, many sensors find themselves redundant because of overlaps in their sensing disks. Hence, redundant sensors should be determined using a *redundancy algorithm*, then their activity (to be in sleep or active mode) should be planned using a *scheduling algorithm*. The two algorithms collaborate to complete the field's coverage while preserving energy and extending the network lifetime. An example is shown in Figure 5.2; although the two sensors s_2 and s_3 are redundant, they can not simultaneously go into sleep mode. A scheduling algorithm should plan their time activity to maintain coverage.

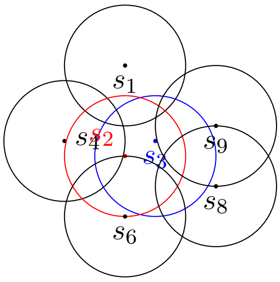


Figure 5.2: An example showing that one of the sensors s_2 and s_3 can be in sleep state.

As already mentioned in the previous section, several CRAs have been proposed in the literature. Nevertheless, most of them are costly ones; the high running time complexity is the common drawback of many CRAs as illustrated in Table 5.1. Indeed, to determine redundancy, in most CRAs, each sensor in the FoI should find out all subregions of all neighboring nodes and check whether each subregion is k-cover or not. This procedure needs many iterative treatments and leads to a high time complexity, hence a considerable energy waste. For instance, in CCP algorithm [111], the sensor should identify all interaction points, inside its sensing disk, then checks whether each intersection point belongs to k active sensors. This procedure requires three nested loops; i.e. a complexity of $O(n^3)$.

Table 5.1: Some CRAs' complexity.

Coverage protocol	**Time Complexity**
CCP [111]	$O(n^3)$
CPP [75]	$O(n^2.log(n))$
ZHA [131]	$O(n^2.log(n))$
VOR [32]	$O(n.log(n))$

On the other hand, the high redundancy determination cost may disturb and delay the entire coverage process, especially when the CRA is join to a periodic scheduling, where the sensor should continually transit between active and sleep states [28, 115].

Coverage and energy preservation issues have been extensively investigated in the literature (e.g. [**?**, 50, **?**, 119]), but, to the best of our knowledge, no work has tack-

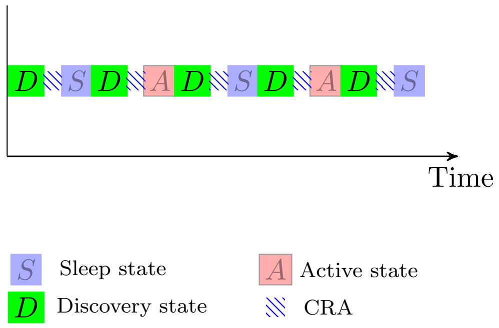


Figure 5.3: Frequent redundancy checks in periodic scheduling schemes.

led the impact of frequent CRA executions and their high complexity on the energy consumption of an EACP. Indeed, this chapter addresses this issue.

5.3 A New k-Coverage Model: Flower Areas determination and k-coverage achievement

We propose, in this section, a new model to complete the k-coverage of a field. It consists on slicing each sensor disk in the field, into sectors. We associate to each sector a sub-region in the sensor disk, called a (*Flower Area*). We prove that the a sensor is k-cover (or simply redundant) if all its sectors are k-cover and each its Flower Area contains, at least, k neighbors. The following questions are addressed:

1. Where *Flower areas* Are exactly located?
2. Are they scattered or contiguous?
3. If a FA form a shape? If yes, how to define it geometrically?

Assuming that each sensor disk is logically divided into i equal sectors. Each sector sec_i is defined by a central angle θ and the two points $begin_i$ and $begin_{i+1}$ (Figure 5.4).

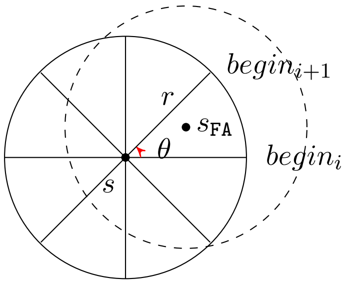


Figure 5.4: Central angle θ and the two points $begin_i$ and $begin_{i+1}$ defining a sector. s_{FA} is a point of the first FA (FA_1).

Table 5.2 summarizes notations which will be used in the rest of the chapter.

Table 5.2: Notations explanation.

Notation	**Explanation**
θ	Sector angle
α	Rotation angle
FA_i	Flower Area of the i^{th} sector
C_t	Circle of a center t
$p(x, y)$	Point in a Flower Area

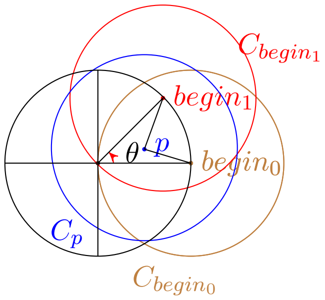


Figure 5.5: Flower Area determination.

5.3.1 Flower Areas Determination

The following Theorem determines exactly the Flower Area points of each sector.

Theorem 1. *Let FA_i be the Flower Area of the i^{th} sector. $p(x, y) \in FA_i$ means:*

$$\begin{cases} (x - r.cos(\theta.(i-1)))^2 + (y - r.sin(\theta.(i-1)))^2 \le r^2 \\ \\ (x - r.cos(\theta.i))^2 + (y - r.sin(\theta.i))^2 \le r^2 \end{cases} \tag{5.1}$$

Proof. We will prove the previous Theorem by induction on the variable h. We consider that the Theorem is correct for h, and we prove it for $h + 1$.

First we check that the property is correct for $h = 1$, means we check the following: $p(x, y) \in FA_1$ means:

$$\begin{cases} (x - r.cos(\theta.(0)))^2 + (y - r.sin(\theta.(0)))^2 \le r^2 \\ \\ (x - r.cos(\theta))^2 + (y - r.sin(\theta))^2 \le r^2 \end{cases} \tag{5.2}$$

By definition, a point $p(x, y) \in FA_1$ means, that p it is the center of a circle C_p whose radius is r and contains the first sector; i.e. it contains the two points $begin_0(0, r)$ and $begin_1(r.cos(\theta), r.sin(\theta))$ (Figure 5.5).

As $|p - begin_0| \le r$ and $|p - begin_1| \le r$ then p belongs, simultaneously, to the two circles C_{begin_0} and C_{begin_1}, whose respective equations are $(x - r.cos(\theta.(0)))^2 + (y -$

$r.sin(\theta.(0)))^2 = r^2$ and $(x - r.cos(\theta))^2 + (y - r.sin(\theta))^2 = r^2$, respectively. Formally: $p(x, y) \in FA_1$ means:

$$\begin{cases} |p - begin_0| \leq r \\ \\ |p - begin_1| \leq r \end{cases} \tag{5.3}$$

$p(x, y) \in FA_1$ means:

$$\begin{cases} p \in C_{begin_0} \\ \\ p \in C_{begin_1} \end{cases} \tag{5.4}$$

$p(x, y) \in FA_1$ means:

$$\begin{cases} (x - r.cos(\theta.(0)))^2 + (y - r.sin(\theta.(0)))^2 \leq r^2 \\ \\ (x - r.cos(\theta))^2 + (y - r.sin(\theta))^2 \leq r^2 \end{cases} \tag{5.5}$$

Hence, the property is verified for h=1.

Now, we assume that the Theorem is correct for h, and we prove it for $h + 1$.

The Theorem is correct for h, means that each sector sec_h is defined by the central angle θ and the two points $begin_h(r.cos(\theta.(h-1), r.sin(\theta.(h-1))$ and $begin_{h+1}(r.cos(\theta.h), r.sin(\theta.h))$, respectively. That is: $p(x_h, y_h) \in FA_h$

$$\begin{cases} (x_h - r.cos(\theta.(h-1)))^2 + (y_h - r.sin(\theta.(h-1)))^2 \leq r^2 \\ \\ (x_h - r.cos(\theta.h))^2 + (y_h - r.sin(\theta.h))^2 \leq r^2 \end{cases} \tag{5.6}$$

We want to prove that the Theorem is correct for $(h + 1)$; i.e. we want to prove that $p'(x_{h+1}, y_{h+1}) \in FA_{h+1}$:

$$\begin{cases} (x_{h+1} - r.cos(\theta.h))^2 + (y_{h+1} - r.sin(\theta.i))^2 \leq r^2 \\ \\ (x_{h+1} - r.cos(\theta.(h+1)))^2 + (y_{h+1} - r.sin(\theta.(h+1)))^2 \\ \leq r^2 \end{cases} \tag{5.7}$$

$p'(x_{h+1}, y_{h+1}) \in FA_{h+1}$ means that the point p_{h+1} is the the image of the point p_i using the rotation rot(O, θ), centered in O and having θ as central angle in anti clockwise direction.

$$p(x_h, y_h) \in FA_h \Rightarrow p'(x_{h+1}, y_{h+1}) \in FA_{h+1}$$

Hence, the relationship between $begin_{h+1}$ and $begin_h$ coordinates are [44]:

$$\begin{cases} x_h = x_{h+1}cos(\theta) + y_{h+1}sin(\theta) \\ \\ y_h = -x_{h+1}sin(\theta) + y_{h+1}cos(\theta) \end{cases} \tag{5.8}$$

By substitution in the equation (5.6), $p'(x_{h+1}, y_{h+1}) \in FA_{i+1}$, means:

$$\begin{cases} (x_{h+1}cos(\theta) + y_{h+1}sin(\theta) - r.cos(\theta.(h-1)))^2 + \\ (-x_{h+1}sin(\theta) + y_{h+1}cos(\theta) - r.sin(\theta.(h-1)))^2 \leq r^2 \\ (x_{h+1}cos(\theta) \quad + \quad y_{h+1}sin(\theta) \quad - \quad r.cos(\theta.h))^2 \quad + \\ (-x_{h+1}sin(\theta) + \\ y_{h+1}cos(\theta) - r.sin(\theta.h))^2 \leq r^2 \end{cases} \tag{5.9}$$

Since

$cos(\alpha+\beta) = cos(\alpha)cos(\beta) - sin(\alpha)sin(\beta)$ and $sin(\alpha+\beta) = cos(\alpha)sin(\beta) + sin(\alpha)cos(\beta)$ [44] and by simplification, $p'(x_{h+1}, y_{h+1}) \in FA_{h+1}$:

$$\begin{cases} (x_{h+1} - r.cos(\theta.h))^2 + (y_{h+1} - r.sin(\theta.h))^2 \leq r^2 \\ \\ (x_{h+1} - r.cos(\theta.(h+1)))^2 + (y_{h+1} - r.sin(\theta.(h+1)))^2 \\ \leq r^2 \end{cases} \tag{5.10}$$

□

The Theorem 1 shows that the Flower Area form a shape which can clearly identifying by only knowing: the sector's index i, the central angle θ and the sensing range r.

5.3.2 Sensing Disk's K-Coverage Achievement

In this section, we describe our methodology for obtaining the sensing disk's k-coverage achievement. To this end, we propose the following Theorem:

Theorem 2. *A sensor disk is k-cover if each one of its Flower areas contains, at least, k active sensors ($k \geq 3$).*

Proof. By definition, each sensor within the FA's sector can entirely cover its sector. In fact, if each flower area in the sensing disk contains at least k active sensors, then all sectors are k-cover and the entire sensing disk is also k-cover. □

5.4 SRA: Sector Redundancy Algorithm

We describe, in this section, an application of the proposed model which is the fully distributed redundancy algorithm, denoted SRA (Sector Redundancy Algorithm). It is composed of two phases: *Sector Flower Area Definition* and *Redundancy Decision phases*. In the former, the FA of each sector is determined while in the latter the redundancy of the sensor is deduced.

5.4.1 Sector Flower Area Definition

As proved in Theorem 1, the Flower Area sub-regions are simply defined by knowing the the sector's index i, the central angle θ and the sensing range r.

5.4.2 Redundancy Decision

The sensor redundancy is decided according to sensors cardinality within each Flower Area. In fact, the sensor is k-cover or simply redundant if the all its Flower Areas contain, at least, k active sensors (see Theorem 1). The SRA algorithm is presented as follows:

Algorithm 3 SRA()

```
Require: $SN(v)$, $k$, $\theta$, $nbsec$
Ensure: $Redundant$
 1: Begin
    {Initialize $SN(v)$, $k$, $\theta$, $nbsec$.}
 2: for all node $u(x_u, y_u) \in SN(v)$ do
 3:   Begin
 4:   for all $i < nbrsec$ do
 5:     $FAdeg[i] := |\{u/u \in FA_i\}|$
 6:   end for
 7:   if $min(FAdeg[]) \geq k$ then
 8:     return Redundant;
 9:   end if
10: end for
    =0
```

Firstly, the neighbors set *SN(v)*, the required coverage degree *k*, the central angle θ, and the number of sector *nbsec*, are initialized (line 1). After identifying all FAs, the coverage degree of each sector $FAdeg_i$ is defined (line 5). It is the number of sensors within each Flower Area. We assume that $FAdeg$ is an array where each case represents a sector coverage degree. The redundancy decision begins when $FAdeg_i$ is compared to the coverage degree required by the application (line 7). If all $FAdeg_i$ are greater than or equal to k, then the sensor is redundant. Hence, the redundancy of a sensor in SRA, is simply known by checking whether sufficient number of neighbors belong to its Flower Areas. Figure 5.6 shows that the sensor s is redundant for $k = 1$.

SRA offers not only a simple and accurate way to determine redundant sensors, but it offers redundancy check with a very low cost as well. Let us compute its complexity: The Algorithm 3 contains one loop with a complexity of $O(n)$ (n is the number of neighbors), the complexity of all the other steps are less than $O(n)$. The overall complexity for SRA is then $O(n)$ lower than many other redundancy algorithms (see Table 5.1).

5.5 SRA-Rot: Sector Redundancy Algorithm with Rotation

Although SRA proves an efficient way to determine redundant sensors, the logical partitioning, as defined in the previous section, needs more information to decide accurately

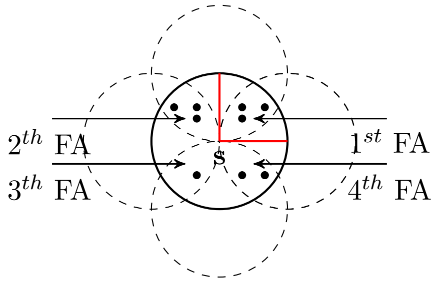


Figure 5.6: The sensor s is redundant bacause $min(FAdeg[]) \geq k$, $(k = 1)$.

about the real coverage degree. For instance, when all sensors fall down outside the defined FA, we can not affirm the sensors' redundancy.

To solve this problem, all possible Flower Areas should be browsed to check whether they contains at least k sensors or not. In fact, a logical rotation with a certain angle value α should be performed to determine all possible FAs of the sensing disk. In the Algorithm 4, the sensor tests the redundancy propriety by calling the SRA procedure (line 5), if the sensor is not redundant, then all FAs will be visited by making consecutive logical rotations (lines 3-8).

Algorithm 4 SRA-Rot()

```
Require: $\alpha$
Ensure: $Redundant$
1: Initialize $\alpha$; {The rotation angle initialisation }
2: $RotAngle = 0$;
3: $Test$:
4: if $RotAngle \leq 2\pi$ then
5:    if $SRA() = \neg\ Redundant$ then
6:       $RotAngle = RotAngle + \alpha$;
7:    end if
8:    goto $Test$
9: end if
   =0
```

5.6 SRA-Rot-k_{lmax}: Sector Redundancy Algorithm with Rotation and Local Maximum Coverage Degree

Given a coverage degree k, both SRA and SRA-Rot can only inform about the redundancy status (redundant or not), but they do not provide any information about the the local maximum coverage degree k_{lmax} provided by sensors. K_{lmax} is defined as the maximum number of neighbors witch can cover each sensing disk. The knowledge of this, is crucial, it helps thereafter to easily deduce the maximum coverage degree of the FoI. This will be detailed in the Section 5.7.2

To determine k_{lmax}, we propose the third CRA called *SRA-Rot-*k_{lmax} (SRA-Rot with Local Maximum Coverage Degree), which is explained in the Algorithm 6.

First, SRA is modified to return the redundancy status and the local maximum coverage degree k_{lmax}. The resulting Algorithm is called SRA-k_{lmax}. It is presented in the Algorithm 5

First, in the line 5 of the Algorithm 6, SRA-k_{lmax}() is called then $min(FAdeg[])$ is checked in the line 6, if it is greater than k_{lmax}, this later is updated (line 7).

Algorithm 5 SRA-k_{lmax}()

```
Require: $SN(v)$, $k$, $\theta$, $nbsec$
Ensure: $Redundant, k_{lmax}$
Begin
{Initialize $SN(v)$, $k$, $\theta$, $nbsec$.}
for all node $(u(x_u, y_u) \in SN(v)$ do
    Begin
    for all $i < nbrsec$ do
        $FAdeg[i] := |\{u|u \in FA_i\}|$
    end for
    $k_{lmax} = min(FAdeg[])$
    if $k_{lmax} \geq k$ then
        return Redundant, $k_{lmax}$;
    end if
    End
end for
End =0
```

Algorithm 6 SRA-Rot-k_{lmax}()

```
Require: $\alpha$
Ensure: $Redundant, k_{lmax}$
 1: Initialize $\alpha$;
 2: $RotAngle = 0$
 3: if $RotAngle \leq 2\pi$ then
 4:     Test:
 5:     if $SRA - k_{lmax}() = \neg\ Redundant$ then
 6:         if $k_{lmax} < min(FAdeg[]) \leq k$ then
 7:             $k_{lmax} = min(FAdeg[])$;
 8:         end if
 9:     end if
10:     $RotAngle = RotAngle + \alpha$;
11:     goto Test.
12: end if
13: return $Redundant, k_{lmax}$; =0
```

An example of the consecutive rotation principle is illustrated in Figure 5.7. In each step, min (FAdeg[]) is calculated considering the next rotation. The final conclusion shows that the sensor s is redundant, precisely it is 2-cover. At this stage, each sensor is aware about its local maximum coverage degree that it can provide in the network. This information will be investigated by the scheduling algorithm to know the maximum coverage degree to cover all the FoI. This idea will be explained in the next section.

5.7 SRA-SPEC: Lightweight k-coverage Protocol Based on Low-Cost Redundancy and Stable-Predictive Scheduling

After determining redundant sensors, k-coverage protocols require a scheduling scheme to decide about sensors' state. A scheduling scheme is composed of rounds, such as the sensor is either sleep or active in each round. Commonly, scheduling techniques are designed to uniformly spend the sensors' energy. However, frequent alternations between the sensor states and the repetitive CRA executions during the scheduling process itself, lead to significant energy waste. To solve this problem, the energy-efficient scheduling called SPEC (Energy-Efficient Coverage Protocol Based on Stable and Predictive Scheduling)[28] is adopted in the design of the new k-coverage protocol. The main idea of SPEC is to reduce the wasted energy by evolving a one-way evolution; i.e. once in active state, the sensor remain there until its exhaustion, both useless transitions between scheduling states as well as unnecessary CRA checks, are prevented. Moreover, to reduce the overall energy waste. In this chapter, SPEC uses SRA-Rot-k_{lmax} as a CRA. Indeed, the new k-coverage protocol is then called *SRA-SPEC*.

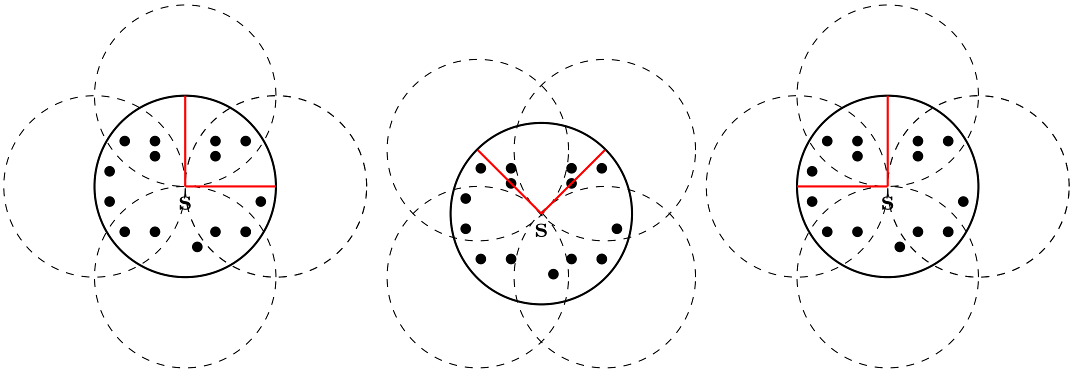
In SRA-SPEC, we assume that sensors operate in four different states, namely: *Discovery*, *Active*, *Sleep* and *Exhausted*.

In the *Discovery* state, the sensor sends and receives messages to discover its neighborhood, whereas in the *Active* state, it actively senses the environment and communicates with other nodes. In the *Sleep* state, the sensor is turned off. Finally, in the *Exhausted* state, the node is about to run out of energy. The notations used by SRA-SPEC are summarized in Table 5.3.

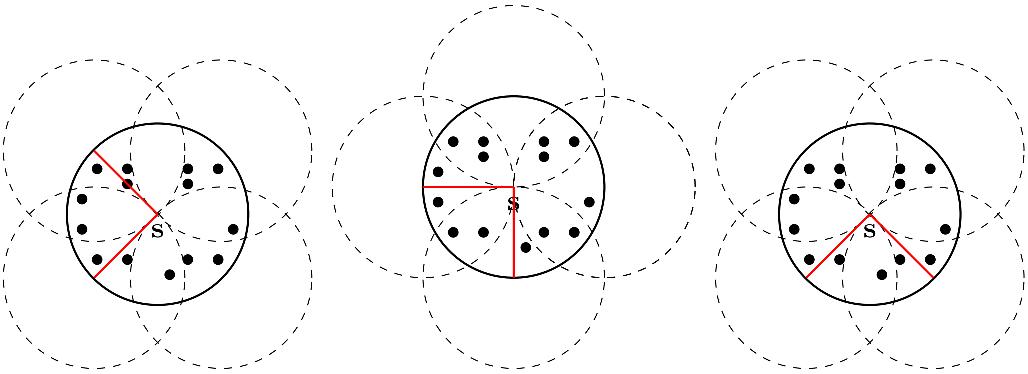
Table 5.3: SRA-SPEC notations.

Notation	**When it is used**
Activity Message (AM)	When the sensor become active
Discovery Message (DM)	To prompt neighbors to construct their neighborhood tables
Discovery timer ($T_{Discovery}$)	To broadcast and receive DMs.
Sleep timer (T_{sleep})	To sleep before beginning a new round
$T_{Ready\_To\_Be\_Active}$	To wait before activating
Activity timer ($T_{activity}$)	To spend in the active state

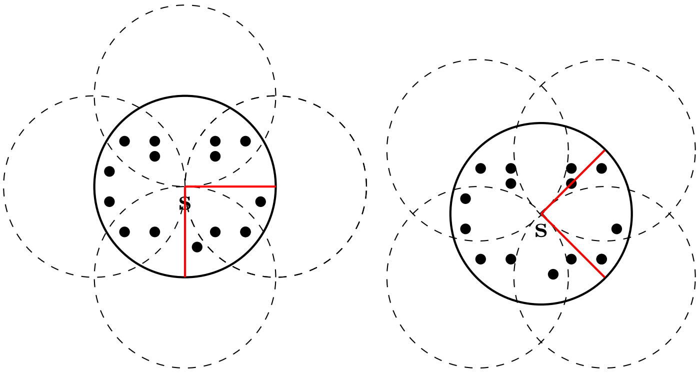
Initially, all nodes are in the *Discovery* state; a discovery timer $T_{Discovery}$ is set up and a discovery message DM is broadcast to prompt neighbors to construct their



(a) $min\ (3,3,2,2) = 2$ (b) $min\ (0,2,1,1) = 0$ (c) $min\ (3,2,2,3) = 2$



(d) $min(2,1,1,0) = 0$ (e) $min\ (2,2,3,3) = 2$ (f) $min\ (1,1,0,2) = 0$



(g) $min\ (2,3,3,2) = 2$ (h) $min\ (1,0,2,1) = 2$

Figure 5.7: Consecutive rotation principle ($k = 1,\ \theta = \frac{\pi}{2},\ \alpha = \frac{\pi}{4}$). Final conclusion: s is redundant, it is 2-cover ($k_{lmax} = 2$)

neighboring tables. Each node runs the first SRA-Rot-k_{lmax} execution which returns the sensor's redundancy status, whether redundant or not.

- **Case 1: The node is redundant;** It means that the sensor disk is completely covered by FAs' neighbors. Thus, the node enters the *Sleep* mode and sets a sleep timer T_{sleep}. A sleeping node should wake up before the exhaustion of the sensor's lowest energy active neighbor located in its FAs.

  Let $T_R(s)$ denote the remaining lifetime of a sensor s according to its available energy. Let S_{FAact} be the set of active sensors in its FAs. The sleep timer T_{sleep} is given by:

  $$T_{sleep} = \min_{\forall s \in S_{FAact}} T_R(s). \tag{5.11}$$

- **Case 2: The node is not redundant;** It means that the node is partially covered. It will probability go to Active state and remain there until exhaustion. In fact, the real sensor activation should be delayed as long as possible because it is an irreversible operation in SRA-SPEC.

  A redundant sensor starts a timer $T_{Ready\_To\_Be\_Active}$ and waits for receiving AM messages from active neighbors that can completely cover its uncovered area. Thus, a redundant node goes to the active state only if no active neighbors can fill its uncovered area. We assume that $T_{Ready\_To\_Be\_Active}$ time is sufficient enough to receive all AM messages from all sensor's active neighbors.

  However, this method is not energy-efficient as the SRA-Rot-k_{lmax} should be executed after each AM reception. To solve this problem, a procedure that check either it is imperative to run the SRA-Rot-k_{lmax} immediately or not, is called. We denote it *the prediction procedure.*

5.7.1 Prediction Procedure

The prediction procedure calls the SRA-Rot-k_{lmax} execution based only on the AM sender location. In fact, if the AM sender belongs to one of the empty FAs, then the SRA-Rot-k_{lmax} is immediately executed because un uncovered part of the sensing disk will certainly be covered by the AM sender. As explained in the Algorithm 7, during time interval $T_{Ready\_To\_Be\_Active}$, the sensor s_i, that we want to check its redundancy, gathers the AM notifications and checks its senders' location (line 3-4). If the AM' sender belongs to an empty FA, s_i immediately executes the SRA-Rot-k_{lmax}. If it is redundant it goes to sleep state, otherwise, the SRA-Rot-k_{lmax} execution is postponed.

If $T_{Ready\_To\_Be\_Active}$ expires without receiving any AM notification, s_i runs the SRA-Rot-k_{lmax} once (line 15). The SRA-Rot-k_{lmax} returns the status *Not Redundant* in the worst case and so the sensor will be activated.

Algorithm 7 Prediction Procedure()

```
while $T_{Ready\_To\_Be\_Active}$ not expired do
  if $Rcvmsg \rightarrow type = AM$ then
    if $\delta(s_i, s_j) \leq r$ then
      $Belong\_To\_Empty\_FA = True$;
      $SRA - Rot - k_{lmax}()$;
      if $Is\_Redundant$ then
        $Cancel\ (T_{Ready\_To\_Be\_Active})$;
        $Goto\ Sleep\ State$;
        $Break$;
      end if
    end if
  end if
end while
if $T_{Ready\_To\_Be\_Active}$ expired then
  $SRA - Rot - k_{lmax}()$;
  $BroadcastAM$;
  $Goto\ Active\ State$;
end if=0
```

Figure 5.8 describes the entire SPEC scheduling process.

5.7.2 The FoI's K-coverage Achievement

The SRA-SPEC scheme, described in the previous section, preserves energy using different rules; it keeps the majority of nodes asleep, delays the activation as long as possible and reduces the CRA frequent executions. Let us prove that it can also preserve the k-coverage of all the FoI. Some properties, which characterizes the intersection of convex sets in Helly's Theorem [12], are used to prove the k-coverage in our model.

Theorem 3 (Helly's Theorem -Intersecting Convex Sets [6] -)**.** *Let E be a family of convex sets in R^n such that any m members of E have a nonempty intersection. Then the intersection of all members of E is nonempty.*

Theorem 4. *A field of interest is k-cover if each one of the existed sensing disks' FAs contains, at least, k active sensors ($k \geq 3$).*

Proof. As illustrated in Figure 5.9, the FoI is composed of a set of intersected disks. The centre of each sensor s_i represents its local maximum coverage degree $k_{lmax(i)}$.

We distinguish two cases:

1. Case 1: $\min\limits_{s_i \in S} k_{lmax(i)} < k$

   When the minimum among all the local maximum coverage degrees is less than the required coverage degree, then the FoI is not k-cover.

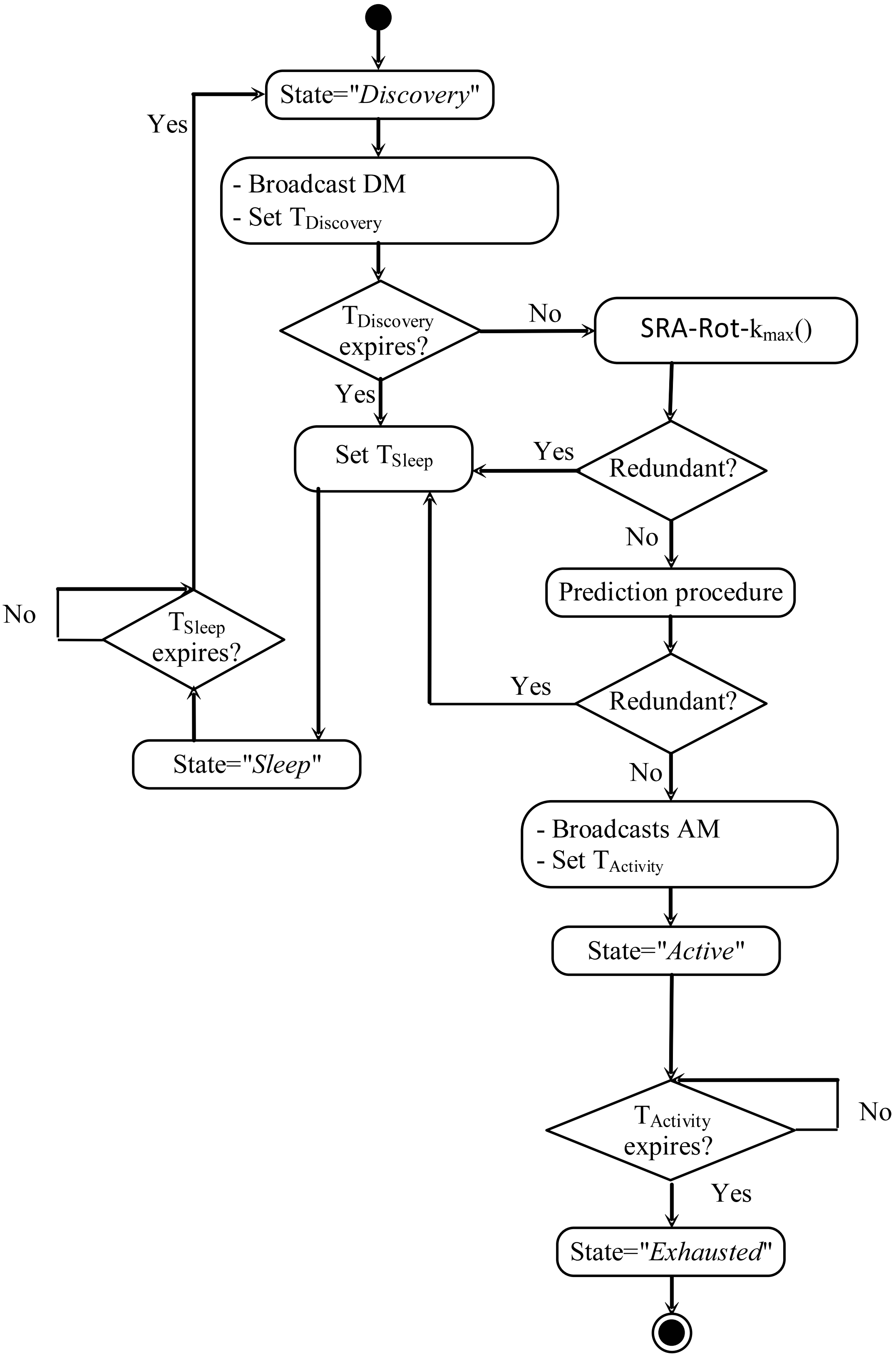


Figure 5.8: SRA-SPEC coverage protocol.

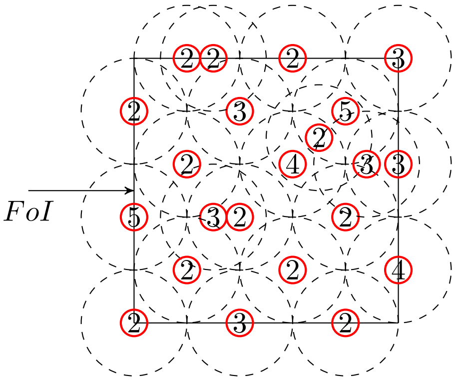


Figure 5.9: The FoI is 2-cover.

2. Case 2: $\min_{s_i \in S} k_{lmax(i)} \geqslant k$

   The intersection of any m neighbor disks is not empty as such proved by Helly Theorem[12]. as depicted in Figure 5.9, each point in the FoI belongs either to a sensing disk, so it is $k_{lmax(i)}$-cover or it belongs to common areas of a set of disks S' ($S' \subset S$), so it is, at least, k'-cover, such us $k' = \min_{s_i \in S'} k_{lmax(i)}$. Hence, each point of the FoI is at least k-cover such as : $k \leqslant \min_{s_i \in S'} k_{lmax(i)} \leqslant \min_{s_j \in S} k_{lmax(j)}$, $(i \leqslant j \leqslant k)$

□

5.7.3 The FoI's Connectivity Achievement

Coverage and connectivity together tell us how well each point in the region is covered and how accurate is the information gathered by connected nodes [45].

In this Section, we prove that like k-coverage, connectivity is also guaranteed using the proposed geometric model.

Definition 12 (***Connectivity***)**.** *A WSN is said to be connected if there is at least one communication path between any pair of sensors [6].*

Theorem 5. *A k-cover field of interest is guaranteed to be connected if the radii R and r of the communication and the sensing of the sensors, respectively, satisfy $R \geq r$.*

Proof. Let u and v be two k-cover sensors in a FoI.

Let u_{f1} be the furthest u's neighbor located in one of its FAs. u_{f1} is k-cover and located, in the worst case, at the the corner of one among the FAs.

Let $u \longrightarrow u_{f1} \longrightarrow u_{f2} \longrightarrow ..... \longrightarrow u_{fh} \longrightarrow v$, a path composed of k-cover sensors, where each sensor in this path, is the furthest FA's neighbor from its previous sensor.

By conclusion, there is, at least, one communication path between u and v ($u \longrightarrow u_{f1} \longrightarrow u_{f2} \longrightarrow ..... \longrightarrow u_{fh} \longrightarrow v$), where the distance between any two consecutive sensors on this path, is less or equal to r.

□

Table 5.4: SRA-SPEC settings.

Notation	Value
Space	100 m x 100 m
Nodes	225
Coverage degree (k)	1-12
Sensing range (r)	20 m
Communication range (r_t)	200 m
MAC	IEEE 802.11
Central angle (θ)	$\frac{\pi}{2}$
Rotation angle (α)	$\frac{\pi}{4}$
Initial energy	200 J
Idle Power	0.75 W
Sleep Power	0.025 W
Transmission Power	1.90 W
Reception Power	1.50 W
Switch Energy	0.6 J
Computation Energy	0.026 J

The result obtained in the Theorem 5 clearly improves the connectivity condition of many other coverage protocol, which requires $R \geq 2r$ (e.g. [111, 75, 15, 14]) or $R \geq \sqrt{3}r$ [6] for the connectivity of k-cover field.

5.8 Performance Evaluation

To assess SRA-SPEC[1] performances, simulation experiments are conducted using the network simulator (NS-2). The simulation parameters are listed in Table 5.4. The nodes' sensing range is set to 20 m and their number is varied between 10 and 225. The nodes are uniformly deployed in 100 m x 100 m area. We assume that a node wastes 0.6 J when transiting from one state to another [95] and 0.026 J to execute each instruction of the redundancy algorithm [35, 73, 10].

The performance of SRA is compared when joining it to a periodic (SRA-Per) and stable-predictive (SRA-SPEC). It is also compared with two other coverage protocol CCP [111] and SCPP [75] which adopt periodic scheduling but with two different redundancy algorithms. The reason behind this comparison is to show the efficiency of joining both low-cost redundancy and stable-predictive scheduling algorithms in one coverage protocol. Table 5.5 summarizes the nomination, the associated redundancy and the scheduling algorithms of the each coverage protocols.

The four schemes are evaluated in terms of the following metrics:

- Energy consumption considering the redundancy algorithm's computation energy;

---

[1] In the rest of the chapter, we write SRA to refer SRA-Rot-k_{lmax} and SRA-SP to refer SRA-SPEC

Table 5.5: The four compared coverage protocols.

Coverage protocol	**Associated redundancy algorithm**	**Associated schduling algorithm**
CCP [111]	CCP [111]	Periodic
SCPP [75]	CPP [75]	Periodic
SRA-Per	SRA	Periodic
SRA-SPEC	SRA	Stable-predictive [28]

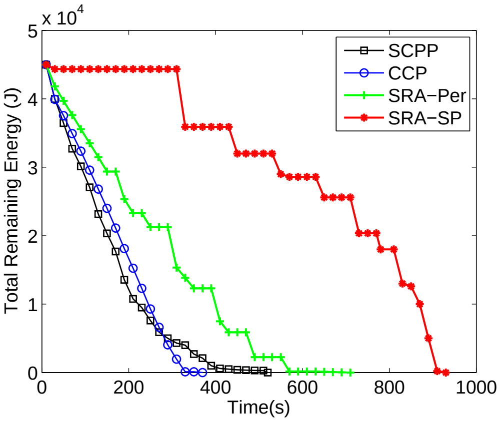


Figure 5.10: Overall energy consumption vs time ($n = 225$, $r = 20$ m).

- Network lifetime;

- Average number of active nodes;

- Coverage degree.

5.8.1 Energy consumption

A sensor consumes energy not only when sending and receiving messages, but even when executing redundancy algorithms and switching between states. Thus the overall energy consumption is evaluated in this four protocols, considering redundancy computation, sensing and communication energies. In Figure 5.10, which illustrates the overall energy consumption, it can be seen that the energy consumption is more pronounced in CPP and SCPP than in our protocols. This is due to two reasons, first because of the high cost of the employed redundancy algorithms ([111]$O(n^3)$, [75]$O(n^2.log(n))$), and second because of the repetitive redundancy executions within a periodic scheduling. Comparing SRA-Per and SRA-SPEC graphs, it can be noticed that even the same CRA is used in our two protocols (i.e. SRA), the energy consumed in the former protocol is higher than in the latter senor status redundancy is determined. This is due to the frequent redundancy execution in periodic schedulings.

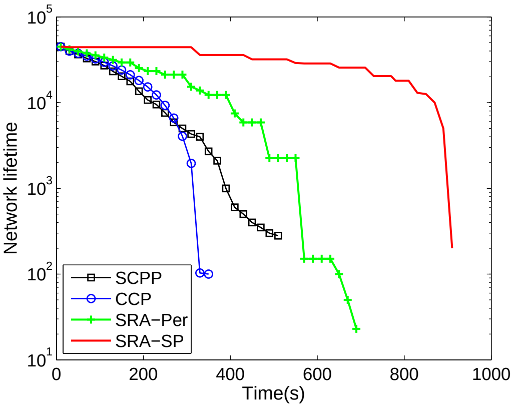


Figure 5.11: Network lifetime (Log scale on y-axis, $n = 225$, $r = 20$ m).

5.8.2 Network lifetime

We define the network lifetime as the rate of nodes alive (i.e. nodes with positive energy) over the time. It is given by the following equation:

$$Lifetime\_Rate_{(t)} = \frac{N\_nodes_{(E>0)}}{N\_nodes_{(t=0)}}. \tag{5.12}$$

where $N\_nodes_{(E>0)}$ is the number of nodes having a positive energy, and $N\_nodes_{(t=0)}$ is the initial number of nodes.

Figure 5.11 (note the logarithmic scale on the y-axis) clearly shows that nodes run out of energy earlier in CCP and SCPP than in our schemes. This can be explained by the high energy consumption induced by state switching, repetitive computation energy (redundancy computation) and communication in these schemes. The figure shows that SRA-Per extends the network lifetime by 46,37% and 24,63% compared to CCP and SCPP, respectively. Furthermore, the stable-predictive scheduling behavior in SRA-SPEC extends the network lifetime by 60,21% and 44,08% compared to CCP and SCPP, respectively. Indeed, the last node dies at 930 s using SRA-SPEC scheme, while it dies at 690 s, 520 s and 370 s when SRA-Per, SCPP and CCP schemes are applied, respectively.

5.8.3 The number of active nodes

Figure 5.12 shows that the four protocols approximately the same number of sensors (average of 20 nodes). This number of sensors is sufficient to cover the sensing field of this experiment. Figure 5.12 shows that once the initial coverage is achieved by CCP and SCPP, this number increases quickly until reaching 130 in CCP and 90 in SCPP, the other nodes have died. The reason behind that is to fill holes generated by the rapid depletion of nodes. Indeed, nodes die more quickly in both CCP and SCPP because of the wasted energy during the repetitive execution of their high complex

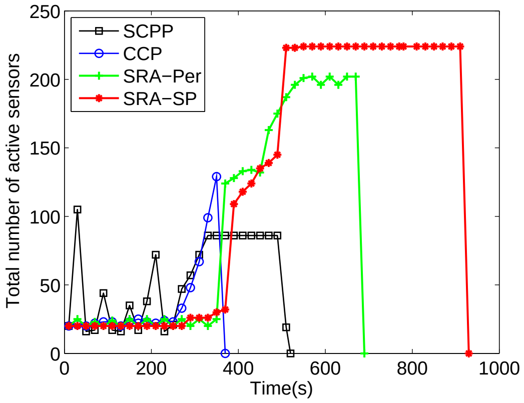


Figure 5.12: Total number of active nodes vs time($n = 225$, $r = 20$ m).

CRAs. On another hand, the initial coverage can be maintained in our scheduling through longer period than in other schemes during ([0 s, 360 s]), then number of active nodes increases until reaching 200 active nodes in SRA-Per and 225 nodes in SRA-SPEC, but the activation period is longer in SRA-SPEC than in SRA-Per thanks to the lightweight energy consumption in SRA-SPEC as explained previously. In fact, sensors in this case merely ensures the monitoring task with the lowest possible energy. By doing so, active nodes are able to monitor the region for long periods.

5.8.4 Coverage degree *(k)*

We evaluate in this scenario, the coverage degree (k) given by the following equation [2] :

$$k = \left\lfloor \frac{N\_nodes_{(state=Active)}}{N\_nodes_{(state=Active,\ t=0)}} \right\rfloor . \tag{5.13}$$

where $N\_nodes_{(state=active)}$ is the number of sensors in the active states while $N\_nodes_{(state=active,t=0)}$ is the number of active nodes at t=0. Figure 5.13 shows that the coverage degree swiftly increases in CCP and SCPP as a large number of sensors should be activated to fill holes caused by the quick nodes death, hence high coverage degree can be reached but only for short periods (k=4 at t=330 s, k=6 at t=360 s) in CCP, and (k=3 at t=200 s, k=4 during [360 s, 520 s]) in SCPP.

Conversely, It also can be noticed that the coverage degree increases to reach high levels and for long periods in our schemes, especially in SRA-SPEC, for instance it reaches k=12 between [700 s, 930 s]) . This is due to the fact that active nodes in SRA-SPEC ensure coverage without executing any redundancy check or transitions, hence they can achieve high coverage degree for longer periods.

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[2] ⌊⌋ is the integer part of the division.

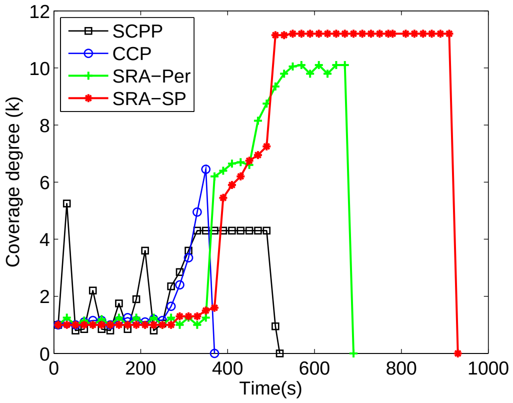

Figure 5.13: Coverage degree ($n = 225$, $r = 20$ m).

5.9 Conclusion and Future Works

We investigated the problem of redundancy detection in WSN with a view to enhance the energy conservation and the network coverage. For this purpose, we proposed SRA and its variants SRA-Rot and SRA-Rot-k_{lmax}, three new redundancy algorithms that determine redundant nodes with a very low cost and independently of k .

SRA-SPEC, the proposed k-coverage protocol that incorporates the previous redundancy algorithms and the stable-predictive scheduling algorithm SPEC, selects a minimum number of sensors to achieve full k-coverage of a field while guaranteeing connectivity between them.

Experimental results confirm that the k-coverage protocol shows better energy and coverage performances compared to other coverage protocols which deploy high cost redundancy and periodic scheduling. Finally, we plan to improve the coverage quality by incorporating heterogeneous sensors in the determination redundancy process, new FAs will be defined in this case. Moreover, we plan to implement the proposed protocols using a sensor-testbed to assess their applicability in real scenarios.

Chapter 6

Conclusion and Future Work

In this thesis, we have dealt with coverage issue in wireless sensor networks. After giving some important concepts, we reviewed the main existing energy-aware coverage approaches then classified them according to their related redundancy and scheduling algorithms. In summary, we notice that these protocols suffer from various shortcomings like repetitive transitions between scheduling states, frequent executions of the redundancy algorithm, redundancy complexity problem, the need of a simple and accurate k-coverage models.

To overcome these various drawbacks, we propose two protocols SPEC (Energy-Efficient coverage Protocol Based on Stable and Predictive Scheduling)[28, 26, 27] and SRA (Sector Redundancy Algorithm)[29, 30]. The former is a new scheduling protocol while the later is a new CRA.

To reduce the switch energy loss, SPEC eliminates many state transitions by adopting a one-way scheduling behavior or continuous sensor activation. The timer of sleeping is adjusted in SPEC according to the active sensors' energies. This prevents the creation of uncovered areas when most sensors are asleep. Finally, a prediction procedure is proposed to prevent the run of unnecessary redundancy executions, hence it reduces the computation energy loss.

SRA is based on a new k-coverage geometric model able to easily check the k-coverage and the connectivity proprieties. SRA is a full distributed redundancy algorithm that quickly discovers the sensor redundancy with a very low time cost (O(n)). The enhancements of SRA, SRA-Rot and SRA-Rot-k_{lmax} explore all possible Flower Areas within the sensing disk, which gives more accuracy to the redundancy assurance and help to smoothly derive the coverage degree of the entire FoI.

Finally, the redundancy algorithm which was considered as a black box in SPEC is replaced by SRA (or its successors). Thus a full k-coverage protocol denoted SRA-SPEC is created. It has many advantages: *i)* It eliminates many transitions between active and sleep states. *ii)* reduces the computation energy as the sensor rarely executes the SRA-Rot eligibility algorithm despite its low complexity. *iii)* Achieves k-coverage and connectivity with a minimum number of active nodes.

Future work:

We plan to extend our study as follows:

- As already seen in SPEC, timer lengths involve its scheduling behavior. A favorable timer management may improve the total network lifetime and the coverage quality. We propose to manage different timers according to the “strength” of the sensor. It is noteworthy that a sensor that covers more blind points in the network should have a shorter activation timer when competing with other sensors.

- Developing a theoretical model to validate stability and prediction strategies is also conceivable as a future work. For instance, we can develop a Markov model describing the evolution through time of the sensor SPEC behavior using a finite continuous time Markov chain with *one absorbing state* (which is the exhausted state in our scheme). Each state of the chain expresses either the sensor mode (Discovery, Active, Sleep, Exhausted) or the sensor action (waiting active message, CRA computing, ...). The chain transitions express the probability of transit from one state to another.

- Improving the proposed k-coverage model by considering other sensors types like external, opposite-external and also heterogeneous sensors. The participation of these sensors will improve the coverage quality. However, new Flowers Areas shapes will occur and should be accurately determined.

- Implementing the proposed protocols using a sensor-testbed to assess their applicability in real scenarios.

- Extending the application of the proposed k-coverage model to other networks like to Wireless Visual Sensor Networks as their field of view (FoV) is also a sector. As an example, redundant visual sensors can be easily detected by investigating the intersected FoV’ Flower Areas.

- Finally, we plan to investigate the proposed optimization schemes of sensing coverage and connectivity in an industrial Internet of Things (IoT) system.

Chapter 7

List of Publications

1. Manel Chenait, Bahia Zebbane, Houda Zeghilet and Nadjib Badache. BSCP: Buckup Scheduling Mecanism for Coverage Perserving in WSNs. In Proc. of the Third International Conference on Sensor Technologies and Applications (SENSORCOMM), pages 473-475, June 2009.
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4. Bahia Zebbane, Manel Chenait and Nadjib Badache. Energy-Efficient Protocol based Sleep-Scheduling for Wireless Sensor Networks. In Proc. of the International Conference on Complex Systems (ICCS), pages 407-412, November 2012.
5. Bahia Zebbane, Manel Chenait and Nadjib Badache. Enhancing the Sensor Network Lifetime by Topology Control and Sleep-Scheduling. In Proc. of the 4th International Conference on SmArt COmmunications in NEtwork Technologies (SaCoNeT), pages 1-5, June 2013.
6. Manel Chenait, Bahia Zebbane, Hamza Belbezza, Hakim Balli and Nadjib Badache. Distributed and Stable Energy-Efficient Scheduling Algorithm For Coverage in Wireless Sensor Networks. In Proc. of the 9th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), pages 418-423, July 2013.
7. Bahia Zebbane, Manel Chenait and Nadjib Badache. GTC: a Geographical Topology Control Protocol to Conserve Energy in Wireless Sensor Networks. In-

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14. Manel Chenait, Bahia Zebbane, Chafika Benzaid and Nadjib Badache. Energy-efficient coverage protocol based on stable and predictive scheduling in wireless sensor networks. Computer Networks 127: 1-12, 2017.
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