Chapter 2

Background

2.1 Introduction

Currently, Wireless Sensor Networks (WSNs) find their applications in various domains of ubiquitous and pervasive computing. This is because of low-cost, low-power consumption, light weight, and advancement in wireless communication technology Abbasi et al. (2017); Gupta et al. (2017); Habibi et al. (2016, 2017); Liao et al. (2015); Qiu et al. (2017); Sakai et al. (2015); Stergiopoulos et al. (2015).

Monitoring of the targets in the given Field of Interest (FoI) is an important task of the WSNs. Physical stimulus (such as heat, light, sound, or pressure) also acts as the targets in WSNs. A sensor node detects, converts the quantity of the physical stimulus into a recordable signal, and digitalizes to produce sensory data. The monitoring of the targets illustrates how well the given FoI is monitored by the deployed sensor nodes. The communication of the sensory data or information of the target to the sink is also an important metric to measure the quality of the WSNs Gupta et al. (2016a); Yang and Chin (2017); Zhang et al. (2010). The sensor nodes in WSNs for monitoring the FoI and communicate the sensory data are powered by the batteries. It is important to reduce the energy consumption of the sensor nodes during the monitoring of the FoI and connectivity of the WSNs. This is because the batteries of such sensor nodes may not be accessible for recharge and replacement.

Targets or physical stimulus in WSNs can be deterministically located inside the FoI, randomly scattered in the FoI, or on the boundary of the FoI. Such targets may change their initial location with time. Based on the requirement of monitoring of the targets, coverage can be classified into three categories: area coverage, point coverage, and barrier coverage Gupta et al. (2017); Rout and Roy (2016b); Weng et al. (2018); Yu et al. (2017). The objective of the area coverage is to monitor the FoI by a set of deployed active sensor nodes. Next, target coverage, which is also known as point coverage, is to monitor the given targets on the fixed locations inside the FoI. Finally, the barrier coverage is used to monitor the border of the given FoI. It helps to detect the intrusion or monitor the movements on the border of the FoI. The *coverage ratio* of the FoI at a given time instance is defined as the ratio of the detected targets to the total available targets in the FoI Gupta et al. (2016b); Liu et al. (2016). The Critical Sensor Density (CSD) of the sensor node is the ratio of the deployed sensor nodes in the FoI to the total area of the FoI.

The existing work in connected WSNs mainly focuses on designing of a *minimum cost WSN* and an *energy efficient WSN* for the desired level of monitoring of targets in the FoI Gupta et al. (2016a, 2013). The work in designing of a minimum cost WSN answering the following question: *What is the CSD of a connected WSN required for the desired level of monitoring of the FoI?*. The authors proposed the analysis for estimating the CSD for the desired level of monitoring of the FoI using connected WSNs. In an energy efficiency WSN, the authors address the following question: *Is a sensor node redundant for the desired level of coverage in a densely deployed connected WSN?*. The authors first estimate the sensing region of a sensor node that is covered by other sensor nodes and turned off the sensor node for reducing the power consumption and enhancing the network lifetime. Designing of a WSN for the desired level of coverage and connectivity considers various issues, such as the dimension of the FoI, kinematics of sensor nodes, heterogeneity in monitoring and communication radii, and shape of sensing and communication regions of sensor nodes Xing et al. (2005).

This chapter reviews the existing work on the design of WSNs for the desired coverage and connectivity. We mainly focus on area or blanket coverage of the FoI. The next section introduces the sensor networks, components of a sensor node, monitoring of the FoI, and network connectivity. We also introduce the sensor coverage models in this section. Issues in WSNs are discussed in Section 2.3. Here, we also discuss some practical challenges in designing of a WSN, such as fault tolerance and border effects. Section 2.4 describes recent solutions for estimating the coverage of the FoI. Such solutions help to design the cost effective and energy efficient WSNs. Coverage and connectivity problems and solutions are discussed in Section 2.5. Finally, the conclusion of the chapter is given in Section 2.6.

2.2 Preliminaries

In this section, we introduce components of a sensor node in WSNs and definitions used in this work. We discuss the binary and probabilistic sensor coverage models.

2.2.1 Components of a Sensor Node in WSNs

A WSN consists of several sensor nodes, they can communicate with each others. The main components of a sensor node are sensing, communication, processing, and storage units. Fig. 2.2 illustrates the components of a sensor node in WSNs.

Sensing Unit

A sensor node in WSNs consists of a sensing unit, which interacts with the physical world around the sensor node. Based on the working principle, sensor nodes in WSNs can be classified into the following categories: active and passive sensor nodes. An active sensor node is a monitoring device used for measuring the signal strength emitted by the sensor node that were reflected by the target. The active sensor requires an extra power source for generating the signals. A passive sensor measures the signal strength emitted from the physical environment. Different from active sensor nodes, the passive sensor does not require any extra power source for generating the signals. It is, therefore the passive sensor nodes consume less energy than active sensor nodes. Fig. 2.1 demonstrates the working of active and passive sensor nodes. Sensor nodes can also be classified into digital and analog, based on a signal produced by them. Digital and analog sensor nodes produce binary and continuous signals, respectively.

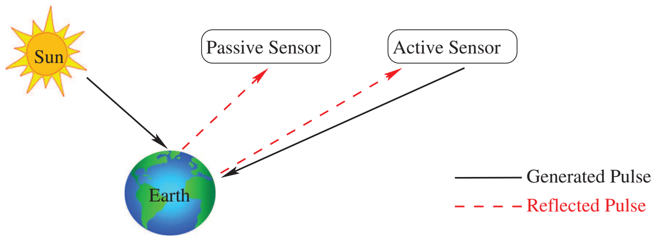

Figure 2.1 Illustration of the working of active and passive sensor nodes in WSNs.

Definition 1 *(Sensing range and region:) The sensing range of a sensor node is defined as the maximum possible distance from the sensor node to a location in the FoI at which an occurred event must be covered by the sensor node. The occurring event in the sensing region of the sensor nodes must be detected by the sensor nodes. The radius of the disc or sphere shaped sensing region is equal to the sensing range of the sensor nodes.*

Communication Unit

Communication unit of a sensor node is responsible for transmitting and receiving the control and data packets. The communication between two sensor nodes in WSNs can be classified into one-way or two-way communication. The literature in WSNs illustrates that the multi-hop communication can significantly reduce the energy consumption in large scale WSNs Djenouri and Bagaa (2015); Liao et al. (2015).

Definition 2 *(Communication range and region:) The communication range of a sensor node is defined as the maximum Euclidean distance between the sensor node and any* *other sensor node, which it is able to communicate. Two sensor nodes in WSNs can communicate with each other only if the Euclidean distance between them is not more then the communication range of the sensor nodes.*

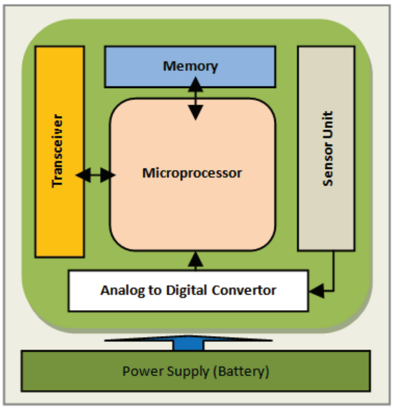

Figure 2.2 Components of a sensor node in WSNs.

Processing Unit

A processing unit in a sensor node interacts with the components and executes the software. Sensor nodes in WSNs have different types of processors based on their tasks, such as microprocessors, microcontrollers, low power digital signal processors, communication processors, and application specific integrated circuits for certain special tasks.

Storage Unit

The current sensor nodes have relatively small and low cost storage unit. Such storage unit saves the instruction sets and sensory data. They most often consist of random access memory, read-only memory, static random-access memory, and non-volatile memory.

2.2.2 Coverage Models

The coverage models in WSNs measure the monitoring capability of the occurring events in the FoI. The coverage model creates a relationship between the Euclidean distance of a sensor node from the physical point and a non-negative real-value number known as *sensitivity*. Based on the detection probability of the events in the FoI, the coverage model in the literature can be classified into the following two categories: binary coverage model and probabilistic coverage model.

Binary Coverage Model

The probability of monitoring of an event in the sensing region of the sensor nodes is constant in binary coverage model. It is also known as Binary Disc Sensing (BDS) model, deterministic disc coverage model, boolean coverage model, or 0/1 coverage model. Let the sensing range of a sensor node s_i is denoted by S_i. The location of a sensor node s_i is denoted by ξ_i. The Euclidean distance between the locations a and b is denoted by $d(a, b)$. $Cov(p, s_i)$ define as an indicator function in BDS model, where s_i is the sensor node and p is the point. The $Cov(p, s_i)$ is given by

$$Cov(p, s_i) = \begin{cases} 1 & \text{if } d(p, \xi_i) \leq S_i \\ 0 & otherwise \end{cases} \tag{2.1}$$

Probabilistic Coverage Model

The binary coverage model requires high accuracy and does not reflect the real behavior of the sensor unit. Thus, the binary coverage model can be extended by adding the probability of monitoring the events, called Probabilistic Sensing Coverage (PSC) model. In PSC model, a sensor node s_i would detect an object at point p with probability $e^{-\omega d(p,\xi_i)^\alpha}$ at a distance less than or equal to the sensing range of the sensor node s_i, where ω denotes the physical characteristic of s_i and α is the path-loss exponent Gupta et al. (2017). Formally, the probability of coverage of a point p by a sensor node s_i in

PSC model is given by:

$$Cov(p, s_i) = \begin{cases} e^{-\omega d(p,\xi_i)^\alpha} & if\ d(p, \xi_i) \leq S_i \\ 0 & otherwise \end{cases} \tag{2.2}$$

Eq. 2.2 illustrates a simple PSC model. The authors in Elfes (1991) used other PSC models, such as Elfes sensing model and Shadow-fading sensing model. Let R be the starting distance of uncertainty in sensor detection, where distance $d(R, \xi_i) < d(S_i, \xi_i)$. In Elfes sensing model, the coverage of a given point p by a sensor node s_i of S_i sensing range is defined as:

$$Cov(p, s_i) = \begin{cases} 1 & d(p, \xi_i) \leq R \\ e^{-\omega d(p,\xi_i)^\alpha} & \text{if } R < d(p, \xi_i) \leq S_i \\ 0 & otherwise \end{cases} \tag{2.3}$$

The Shadow-fading sensing model is given by:

$$Cov(p, s_i) = \begin{cases} f\left(\frac{10\alpha \log(d(p,\xi_i)/S_i)}{\sigma}\right) & if\ d(p, \xi_i) \leq S_i \\ 0 & otherwise \end{cases} \tag{2.4}$$

2.2.3 Classification of Coverage in WSNs

Based on the requirement of monitoring of the targets, coverage can be classified into the following types:

• The area coverage, which is also known as blanket coverage, is to monitor the FoI by a set of deployed sensor nodes in WSNs.

• The target coverage, which is also known as point coverage, is to monitor the given targets in the FoI. The target coverage reduces the energy consumption because it monitors only the given location of targets in the FoI.

• The main objective of barrier coverage concerns with constructing a barrier for intrusion detection. If any intrusion takes place along the barrier, then sensor nodes can detect the intrusion.

2.3 Issues and Challenges

In this section, we discuss the following design issues in WSNs for coverage problem: deployment methods, sensor node types, the mobility of sensor nodes, the dimension of the FoI, solution approaches, fault tolerance, network connectivity, and maximize the network lifetime.

2.3.1 Deterministic vs. Random Deployment of WSNs

Deployment methods in WSNs solve the following problem: *How to deploy the sensor nodes in the FoI so that the targets are covered and sensor nodes can communicate the sensory data to the sink node?*. Based on the possibility of the placement of the sensor nodes, the deployment of WSNs can be categorized in two different ways: random deployment and deterministic deployment Alduraibi et al. (2016). The deterministic deployment method, also known as grid deployment, locates the sensor nodes in a pre-estimated location in the FoI. The deterministic deployment of sensor nodes can be divided the FoI into regular (*i.e.*, square, triangle, and hexagon) pattern and irregular pattern Gupta et al. (2015b). Some applications, which are permitted for deterministic deployment of sensor nodes, the positions of the sensor nodes can be optimized to achieve the desired level of target monitoring, connectivity in WSNs, minimize the network cost, and maximize the residual energy of the sensor nodes. However, some scenarios of WSNs such as inaccessibility (enemy region, tough terrain) or cost of deployment, are not permitted to have a deterministic deployment.

2.3.2 Homogeneous vs. Heterogeneous WSNs

A homogeneous WSN consists of equal ability sensor nodes in term of sensing and communication radii, energy, storage, and software, etc. The coverage and connectivity of WSNs in a homogeneous environment has been studied very well in Alam and Haas (2006); Aslam and Robertson (2010); Berman and Calinescu (2004); Boukerche and Fei (2007); Gao et al. (2015). However, it is not feasible or practically possible to keep homogeneity in the whole network life. The following issues show that to keep the homogeneity in WSNs is not feasible or impractical.

- The first issue is the cost of the WSNs. A high cost sensor node consists of the high computational power. A WSN is said to be cost effective if it consists of low cost and high cost sensor nodes for simple and complex tasks, respectively.
- Due to fast changes in computer architecture, it is very infeasible to find the same type of sensor nodes for re-deployment of WSNs. The re-deployment of sensor nodes is, therefore, another issue for creating the heterogeneity in WSNs.
- Energy-efficiency in WSNs also creates the heterogeneity in WSNs. Some sensor nodes adjust their communication and sensing range based on the requirement of the WSNs. Such adjustment in the ranges helps to reduce the energy-consumption, but creates the heterogeneity in WSNs Gupta and Rao (2016).

2.3.3 Static vs. Mobile WSNs

The sensor nodes in static WSNs do not change the locations. A WSN is said to be mobile if the sensor nodes change the locations based on the requirement of the network. The mobility of sensor nodes in WSNs helps to enhance the quality of services of WSNs.

A high cost sensor node in mobile WSNs is sufficient to monitor the FoI in the different time and therefore helps to reduce the cost of the network. The mobility in WSNs also creates a new research issue known as path planning of the sensor nodes. Such research mainly focuses on to find a path of the sensor node from its current location to the next destination location based on the requirement of the network Birkeland (2017); He and Zhang (2016); Lalouani et al. (2015); Li and Shen (2015); Tolba et al. (2016); Zhang et al. (2017a).

2.3.4 Directional vs. Omni-directional WSNs

Directional WSNs consists of the sensor nodes whose sensing region is bounded in a fixed direction. The directional sensor node cannot detect the targets in other directions, even the distance between the target and the sensor node is not more than the sensing range of the sensor node. Differs from the directional WSNs, an omni-directional sensor node monitors equally in all directions. The main advantages in directional WSNs are energy-efficient and low interference problem. An omni-directional communication region based sensor node can communicate with other sensing nodes only if the locations of the sensor nodes lie inside the communication regions of the sensor nodes Gonen et al. (2015); Scott et al. (2016); Wang et al. (2015); Yu et al. (2015); Zhang et al. (2016a).

2.3.5 Two-dimensional vs. Three-dimensional WSNs

The shape of the FoI plays an important role in selecting the appropriate sensor nodes and existing solutions for coverage and connectivity problems. Most of the existing research work in coverage and connectivity issues focus on two-dimensional WSNs which assumes that the sensor nodes are deployed in two-dimensional FoI. However, most of the real world WSNs application scenarios support the three-dimensional model such as underwater monitoring, multi-storage structure monitoring, tree height monitoring, etc. The three-dimensional WSNs is more suitable for monitoring the targets in such scenarios Gupta et al. (2016a); Khalfallah et al. (2016). The following points illustrate that the existing work for two-dimensional WSNs cannot be extended for solving the coverage and connectivity problems in three-dimensional WSNs.

- The existing work uses computational geometry based approaches such as Voronoi diagram or power diagram, for estimating the redundancy of the sensor nodes in densely deployed WSNs. The time and computational complexities of such computational geometry based approaches are very high in case of three-dimensional and therefore not suitable for low cost sensor nodes.

- The number of neighbor sensor nodes is very high in three-dimensional WSNs as compare to the two-dimensional WSNs. Therefore, the memory based protocols in WSNs are required huge space for saving the neighbors information in three-dimensional WSNs.

- The probabilistic based approaches for solving the coverage and connectivity problems assume that the FoI does not consider the border. It is suitable only if the ratio of the border region and the total region is very small. However, it is not true. The border effects in three-dimensional WSNs is very high.

Such points illustrate that the shape of the FoI is an important issue and the coverage and connectivity problems in three-dimensional WSNs must be addressed in future research.

2.3.6 Centralized vs. Distributed Approaches

Based on the WSNs topology and application scenarios, the existing solutions for solving the coverage and connectivity problem can be classified into the following two categories. The centralized solution consists of a high end sensor node which collects the global information or sensory data, process and runs the algorithm, and communicates the solution to the sensor nodes. The distributed solution does not require a high end node. All sensor nodes in the WSNs locally collect the sensory data from their neighbours, solve the problem, and share the solution. The distributed solutions work well when the network is more dynamic (such as mobile WSNs) and size of the network is large Yang et al. (2015). The utility of the centralized and distributed approaches in WSNs depends up to the network scenarios and applications.

2.3.7 Fault Tolerant in WSNs

A WSN may become faulty due to the hardware issues, environmental factors, or human interference. Various techniques are proposed in the literature for handling the faults in WSNs. A common solution for handling the faults in WSNs is to deploy extra sensor nodes and use them as the backup during faulty time. Such solutions use the term *redundancy degree*, which is defined as the number of sensor nodes cover a target in the FoI. A FoI is said to be k-covered If each point in the FoI is covered by atleast k sensor nodes in WSNs, where $k \geq 1$ Willson et al. (2015). The *k-coverage ratio* of the FoI is equal to the fraction of the k-covered points to the total points in the FoI.

2.3.8 Maximizing Network Lifetime

Maximizing the network lifetime is expected by many monitoring applications. However, it is difficult to recharge the randomly deployed battery powered sensor nodes. The exiting solutions for coverage and connectivity problem presented various techniques for prolonging the network lifetime while ensuring the desired quality of services. A common technique for maximizing the network lifetime, is to schedule the redundant sensor nodes into sleep state while preserving the network property (*e.g.*, network connectivity and desired coverage degree) Gupta et al. (2013); Harrison et al. (2015); Mtawa et al. (2015).

2.3.9 Border Effects

Some application scenarios of WSNs support only random deployment of sensor nodes, such as deployment of sensor nodes in forest region, chemical plant monitoring, nuclear plant monitoring, etc. Due to the random deployment of sensor nodes, some sensor nodes are placed near the boundary of the FoI. The sensing region of such sensor nodes is not fully useful for monitoring the FoI. Such partial useful sensing region of the sensor nodes reduces the utility of WSNs. The literature in WSNs for coverage and connectivity considers this issue and called as border effects Gupta et al. (2017); Zhang et al. (2016c).

2.4 Approaches for Solving Coverage Problems

In this section, we review the existing work that is used for solving the coverage problems in WSNs. We classify the existing work into the computational geometry and probabilistic based approaches. We considered the design issues and challenges as discussed in the previous section.

2.4.1 Computational Geometry Based Approaches

Voronoi diagram, Delaunay triangulation, and Power diagram are widely used for solving the WSN problems such as coverage estimation, reducing the overall memory requirement, preventing the transmission of redundant communication messages, and optimization in WSNs Abbasi et al. (2017); Argany et al. (2010); Bai and Heath (2013); Carbunar et al. (2004, 2006); Ghosh (2004); Habibi et al. (2016, 2017); Liao et al. (2015); Mahboubi and Aghdam (2017); Mahboubi et al. (2014a,b); Miah et al. (2015); Mohseni et al. (2016); Qiu et al. (2017); Sakai et al. (2015); Schwager et al. (2017); So and Ye (2005); Stergiopoulos et al. (2015). This section reviews the existing work that solves the coverage and connectivity problems using computational geometry approaches.

Two-dimensional WSNs

Carbunar *et al.* Carbunar et al. (2004, 2006) addressed the problem of determining and eliminating the coverage redundancy in a given WSN with a view to prolong the lifetime of WSNs. They utilized Voronoi diagram to determine the coverage of homogeneous WSNs and Multiplicatively Weighted Voronoi Diagram (MWVD) for heterogeneous WSNs. The authors also solved the coverage-boundary detection problem. The objective of the problem is to detect where a given sensor node is located near the boundary of the FoI, called as a boundary sensor node in the network. Such sensor nodes create the border effects in the WSNs. The authors used Voronoi diagram and proved that a sensor node is the boundary sensor node if and only if there exists some non-overlapping region between the Voronoi polygon region and the sensing region of the sensor node. Let n be the number of sensor nodes in the network. The time complexity of the proposed work is $O(nlogn)$.

d-dimensional WSNs

So *et al.* So and Ye (2005) used Voronoi and power diagram for solving the coverage problem in d-dimension WSNs, where $d \geq 1$. Authors determined whether a given FoI is sufficiently k-covered by a given set of n sensor nodes in $O(n\,log\,n + nk^2)$ time. The solution of this problem will run in $O(n^3)$ and $O(n^4)$ time for two-dimensional and three-dimensional WSNs. Moreover, this approach allows handling sensing regions whose shape cannot be conveniently modeled as Euclidean ball. This algorithm is used for k-coverage verification of two-dimension and three-dimension WSNs. However, it is a centralized approach, so may not scale well for larger scale WSNs. Alam and Haas Alam and Haas (2015) proposed a three-dimension WSN deployment pattern for the coverage problem. The proposed work is based on Voronoi tessellation. The work created the truncated octahedral cells and concluded that the packing by a truncated octahedron provides a maximum volumetric coefficient or the minimum number of sensor nodes.

Coverage and connectivity in WSNs

Jiang *et al.* Jiang et al. (2005) considered a coverage and connectivity problem, which aim to construct minimal connected cover sets that are sufficient for the desired quality of service in WSNs. The basic idea is to calculate the cover set and then make it connected.

They proposed an algorithm to select minimum required sensor nodes for the desired level of coverage using Voronoi tessellation. The main advantage of the proposed work is to prolong the network lifetime. However, it is a centralized algorithm and therefore not suitable for a large scale WSN. The authors also proved that if communication range is less than twice the sensing range, the WSNs is not connected. Authors solved this problem by designing a steiner minimum tree based algorithm to compute the minimal set of additional sensor nodes needed to make a connected cover set.

Sensor nodes location-free solutions for coverage

A localized Voronoi diagram based distributed algorithm for solving the coverage and redundancy eliminating problem has been proposed by Boukerche and Fei (2007). A sensor node in the network calculates the location information of neighbor nodes by using the directional antennas. The advancement of the proposed work that it does not require any global location and therefore reduces the power consumption and cost of the location finding devices. The algorithm used Voronoi tessellation and discovered fully sponsored sensor nodes without error. Such sponsored sensor nodes are identified by estimating the coverage redundancy of Voronoi cells. The Voronoi cells in the FoI are created by using the deployed sensor nodes. Let m be the number of sites involved in generating such Voronoi cells. The time complexity of the proposed work is $O(mlogm)$ which is less than the work proposed in Carbunar et al. (2004, 2006).

Mobility in WSNs

Authors in Boukerche and Fei (2007); Carbunar et al. (2004, 2006); Jiang et al. (2005); So and Ye (2005); Wei Wang and Chua (2007) assumed that the sensor nodes are static and locations of randomly deployed sensor nodes are fixed. The random deployment of sensor nodes creates a non-uniform sensor node density scenario in the FoI, *i.e.*, some part of the FoI is covered by more number of sensor nodes and others are uncovered. The

Table 2.1 Illustration of the computation geometry based approaches for solving the coverage problems.

Issue/ Paper	Deployment of Sensors		Node Type		Mobility of Nodes		FoI Dimension		Solution Approach		Fault Tolerant	Connectivity	Energy Efficient	Border Effect
	Random	Deterministic	Homogeneous	Hetrogeneous	Static	Mobile	2-D	3-D	Centralized	Distributed	k-Coverage			
So and Ye (2005)	√		√		√		√	√	√		√			√
architecture Carbunar et al. (2004)	√		√		√		√			√				
Carbunar et al. (2006)	√		√	√	√		√			√	√		√	√
Ghosh (2004)	√		√		√		√			√				
Ghosh and Das (2005)	√		√		√	√	√			√		√		
Jiang et al. (2005)	√		√		√		√		√			√		
Boukerche and Fei (2007)	√		√		√		√			√				
Wang et al. (2006)	√		√			√	√			√				
Alam and Haas (2006)	√	√	√		√		√	√						
Zhang (2012)	√		√		√		√			√				
Stergiopoulos et al. (2012)	√		√		√	√	√			√				
Habibi et al. (2017)	√		√	√		√	√			√				
Qiu et al. (2017)	√					√	√			√	√			
Abbasi et al. (2017)	√		√		√	√	√		√					
Habibi et al. (2016)	√		√			√	√			√				
Sakai et al. (2015)	√		√		√		√	√		√	√			
Liao et al. (2015)	√		√			√	√		√			√		
Stergiopoulos et al. (2015)	√		√		√		√			√				
Dash and Dasgupta (2017)	√		√		√	√	√			√				
Yang and Chin (2017)	√		√		√	√	√			√		√	√	
Wei et al. (2017)	√		√		√		√				√	√	√	
Yu et al. (2017)	√		√		√	√				√	√			
Deng et al. (2017)	√		√			√	√			√			√	
Mahboubi and Aghdam (2017)	√			√		√	√			√				
Pananjady et al. (2017)	√		√		√		√		√					
Shahidehpour and Wu (2016)		√	√		√		√		√					

environmental factors, such as wind and water flow, are also the causes of non-uniform sensor node density in the FoI. Sensor node mobility provides a solution for creating the consistency in sensor node density. The movement of sensor nodes in random deployment is addressed in Ghosh (2004); Ghosh and Das (2005); Mohseni et al. (2016); Wang et al. (2006). The work in Ghosh (2004) assumed that the WSNs consist static and mobile sensor nodes. The static sensor nodes are randomly deployed in the FoI and able to calculate their own and neighbors location information. The authors used a centralized Voronoi diagram to estimate the location of uncovered region in the FoI and the required number of sensor nodes for providing the desired level of quality of services. The proposed work deployed the required mobile sensor nodes for filling the uncovered region.

The sensor nodes in mobile WSNs have the ability to move in order to enhance overall coverage. The movement of sensor nodes in random deployment is addressed by Wang *et al.* Wang et al. (2006). The authors proposed three Voronoi based distributed self-deployment algorithms to move mobile sensor nodes from a redundantly covered region to uncovered region in an iterative way. The Vector-based algorithm moves the sensor nodes from high density to low density region on the FoI. The algorithm moves a sensor node from its current position to a new position or destination only if the movement increases the local coverage within its Voronoi cell. If local coverage is not increased, the sensor node selected the middle point position as new position, where the middle point is the point between its current location and the destination. Such middle point acts as the current location in next iteration of the algorithm. The proposed algorithm iteratively runs till the region is not covered or movement of sensor nodes does not increase the coverage of the FoI.

In the mobile WSNs, the number of neighboring and the locations are changed with time. Therefore, the communication overhead for maintaining the connectivity in the mobile WSNs is very high as compared to the static WSNs. The authors in Liao et al. (2015) addressed the connectivity problem in mobile WSNs. The proposed work illustrated the impact of the mobility of sensor nodes on coverage and connectivity. The authors used clique partition and Voronoi partition for estimating the minimum required movement of the sensor nodes for the desired level of target coverage and network connectivity. The authors in Habibi et al. (2017) used a gradient-based nonlinear optimization approach to find a target point for each sensor node such that the local coverage increases as much as possible. Let Π_i, $D(\xi_i)$, and $\varnothing(q)$ denote the Voronoi polygon (or cell) of sensor node s_i, sensing region of s_i, and priority function of a target point q, respectively. The authors addressed the following coverage maximization problem:

$$\max_{\{\xi_i,\Pi_i\}_{i=1}^{n}} \sum_{i=1}^{n} \int_{\Pi_i \cap D(\xi_i)} \varnothing(q)dq, \tag{2.5}$$

$$s.t. : \xi_i \in \Pi_i, 1 \leq i \leq n.$$

Farshid *et al.* Abbasi et al. (2017) addressed the coverage problem in mobile WSNs. The proposed approach ensures the local optimum coverage over the blankets leading to the partitioning of the dynamic region by dividing it into multiple subregions associated with multiple deployed agents. The work in Habibi et al. (2016); Mahboubi and Aghdam (2017) investigated the effect of measurement error on the desired level of coverage of the FoI in mobile WSNs. The authors also presented a distributed deployment strategy, which uses information on error bounds in order to move the sensor nodes to appropriate locations Habibi et al. (2016). The authors in Qiu et al. (2017) proposed a Distributed Voronoi-based Cooperation (DVOC) mechanism for full coverage using mobile sensor nodes. In this scheme, each sensor node builds its own local k-order Voronoi diagrams and helps other nodes to detect holes within their own diagrams. Let a random point p in the given region Ψ. The randomly deployed WSN consists of S homogeneous sensor nodes. The authors say that the region is k-covered by the deployed sensor nodes if

$$\forall p \in \Psi, \exists S \subseteq \mathbb{S}, where\, |S| \geq k \;\; s.t. \;\; p \in \bigcap_{i \in S} D(s_i) \tag{2.6}$$

2.4.2 Probabilistic approaches for coverage in WSNs

In random deployment, the sensor nodes are deployed uniformly at random in the FoI. Let N number of sensor nodes are uniformly and independently scattered in the region Ψ and location of sensor nodes can be modulated by a stationary Poisson point process. The density of Poisson point process is denoted as λ, which equals to the ratio of the sensor nodes to the area of the FoI Ψ, *i.e.* $\lambda = N/|\Psi|$. When N is large, the number of sensor nodes in Ψ, will be Poisson distributed with parameter $\lambda\Psi$:

$$P(N = k) = \frac{e^{-\lambda\Psi}(\lambda|\Psi|)^k}{k!}. \tag{2.7}$$

The exiting research work based on the probabilistic approaches used Eq. 2.7 for solving the coverage problem in WSNs.

Maximizing network lifetime

Tian *et al.* Tian and Georganas (2004) proposed a sleep-scheduling algorithm, which reduces energy consumption by making some redundant sensor nodes fall asleep. Authors proposed three off-duty eligibility schemes for selecting the redundant nodes in the WSN. The proposed schemes are location-free and do not need location information during the scheduling of sensor nodes. The Neighbor Number Based (NNB) scheme makes a given sensor node as an off-duty node if it is covered by their neighbors. NNB scheme used the distance of neighbors to calculate the intersection area of the given sensor node and its neighbors. The nearest-neighbor based scheme used only the number of neighbors to calculate the intersection area of a given sensor and its neighbors by using composite Simpsons rule. The probability-based sensor node scheduling scheme used the Poisson process to verify that a sensor node is eligible for off-duty or not. The scheme does not need to know any kind of neighbor information to determine its status. This feature reduces the communication cost to coordinate the scheduling between neighboring sensor nodes. However, it does not ensure the full coverage of the FoI. As compared to the nearest-neighbor based scheme, the NNB scheme generates more off-duty sensor nodes for the desired coverage. Therefore, the NNB prolongs, more lifetime of the network as compared with others.

The authors in Gupta et al. (2016b) addressed the following problem: *How to identify the sensing region of a sensor node that is overlapped with its neighbor sensor nodes in three-dimensional WSNs*?. The proposed work considered fault-tolerant WSNs, *i.e.*, each event in the given region is simultaneously monitored by atleast k sensor nodes, where $k \geq 1$. The work also relaxed the assumption of the equal monitoring and communication radii and therefore suitable for heterogeneous WSNs.

Tian and Georganas Tian and Georganas (2002) addressed the problem for reducing the energy consumption while maintaining the desired quality of services of WSNs. The proposed method used the location information of the sensor nodes. Each sensor node collects the location information of their neighbor sensor nodes for estimating the redundant sensor region. The authors defined the network lifetime as maximum possible time when the network is able to provide the services. The network lifetime is divided into the rounds. The duration of each round is fixed. A sensor node collects the information about their neighbors and estimates the redundantly sensing region of the sensor node. Such redundant sensing region is called the sponsored section of the sensor node. A sensor node is redundant for coverage if the entire sensing region of the sensor node is covered by its neighbor sensor nodes. Fig. 2.3 illustrates that the sensor node s_1 is a redundant sensor node. The redundant sensor node broadcasts the sleep message and turns its sensing radio off. Before the beginning of a new round, all sensor nodes come in active state and repeat the above process. The proposed method prolongs the life of network using the sleep and active states of the sensor nodes. The main limitation of the proposed work is that it considered only coverage of the FoI. The network connectivity is also an important issue in WSNs which is not considered in this work.

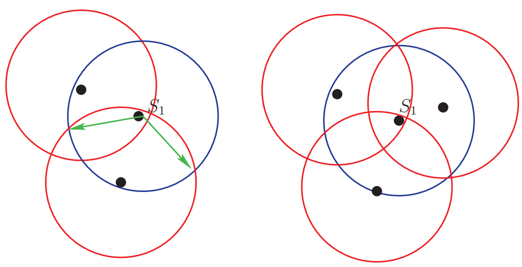

Figure 2.3 Sponsored coverage for redundancy check Tian and Georganas (2002).

Critical sensor density of sensor nodes

The Critical Sensor Density of sensor nodes (CSD) is the ratio of the sensor nodes required for monitoring the FoI to the area of the FoI. The CSD helps to estimate the cost of the WSNs for the desired level of monitoring and connectivity. Zhang and Hou Zhang and Hou (2004) assumed that the shape of the FoI is squared with d side length. The authors proposed the analysis for estimating the CSD for k-coverage of the FoI. Authors assumed that the deployment of sensor nodes uses Poisson point processes. The main limitation of the proposed work is that it does not consider the border effects of the FoI. They assumed that the FoI is Toroidal shaped, which is not relevant to the practical application scenarios. The CSD is given by $log\, d^2 + (k+1) log\, log\, d^2 + c(d)$ and $c(d) \rightarrow \infty$ is the necessary and sufficient condition for the desired k level coverage of d side length squared shaped FoI.

Kumar et al. (2004) proposed the analysis for estimating the number of sensor nodes for desired level of monitoring. Authors assumed that the redundant sensor nodes are eligible for sleep state. The authors studied asymptotic k-coverage and found that the coverage depends on the value of the function

$$c(n) = \frac{np\pi R_s^2}{log(np)}, \tag{2.8}$$

where n is the large number of sensor nodes and p is the probability that a sensor node is active. The authors used three different deployment models for deriving the sufficient value of $\frac{np\pi R_s^2}{log(np)}$ for ensuring the full coverage. The authors proved that each pleast one sensor node. Some applications of WSNs do not require complete coverage of the FoI. Example of such applications are environmental information monitoring, forest temperature monitoring, or river water level monitoring, where each point of the FoI is not required to monitor. Such applications require partial coverage of the given region where the coverage ratio of the FoI is less than unity. Gupta and Rao (2016) presented a Demand-Based Coverage and Connectivity-preserving Routing (DBCCR) protocol for maintaining the required level of monitoring of the FoI in a connected WSN. A sensor node changes ON and OFF states based on the requirement of the users. The protocol uses relay sensor nodes based technique, known as local route optimization with power control, for reducing the energy consumption during transmission of sensory data. The proposed work does not require any center control or location information of sensor nodes for maintaining the coverage of the FoI in a connected WSN. From Kumar et al. (2004), the point in the FoI is simultaneously monitored by k sensor nodes with high probability if

$$c(n) \geq 1 + \left[\phi(np)\left(1 + \sqrt{plog(np)}\right) + k\ log\ log(np)\right] / \ log(np), \tag{2.9}$$

where n is the large number of sensor nodes. The deployment of sensor nodes in WSNs are assumed to a Poisson point process that followed by a Bernoulli-style active and inactive process. In a large value of n, the Bernoulli process is still a Poisson point process. Therefore, a FoI is k-covered if

$$c(n) \geq 1 + [\phi(np) + k\ log\ log(np)] / \ log(np). \tag{2.10}$$

The deterministic deployment of sensor nodes assumes that the sensor nodes are manually deployed in the FoI. Some WSNs application scenarios assume that the deterministic deployment required more number sensor nodes than random deployment in WSNs for desired coverage and connectivity Zhang and Hou (2006). The authors assumed that all sensor nodes are the same type and the sensing region equals to the unity. Let the area of the FoI is denoted by A, where $A \to \infty$. They proved that the FoI is k-covered if $np = log\, A + 2k\, log\, log\, A + c(A)$, $(-log(1-p))n/A = log\, A + 2k\, log\, log A + 2\sqrt{-2\pi log\, A\, log(1-p)} + c(A)$, $c(A) \to \infty$, and $A \to \infty$. In this chapter, authors used the linearity property of expectations and Markov inequality. To characterize the coverage properties of large-scale randomly distributed WSNs, the authors assumed the boolean sensing model, where probability of monitoring of an event is equal to unity or zero Liu and Towsley (2004). They defined three coverage measures: area coverage, node coverage, and detectability. Authors proved that if the density of sensor nodes are less, the ratio of redundant sensor nodes that can be turned off without reducing coverage area is small.

Mobility in WSNs

The authors in Chellappan et al. (2007a) introduced flip-based sensor nodes for coverage of the given FoI. The flip-based sensor nodes can partially mobile sensor nodes, *i.e.*, a flip-based sensor node moves from the deployed location to a fixed destination location once in their life. After this movement, the sensor node converts in static sensor node. The advantage of such sensor nodes is to reduce the communication overhead for maintaining the connectivity in the network. The work proposed sensor node mobility technique for enhancing the coverage of the FoI. The authors in Chellappan et al. (2007b) extended the work and proposed a distributed heuristic algorithm for making the equal sensor node density in the whole FoI. The work in Chellappan et al. (2007a) and Chellappan et al. (2007b) has the limitation that they do not ensure the optimality of the movement of sensor nodes and coverage of the FoI.

A Hybrid network structure known as push-relabel structure is used by Wang *et al.* Wang et al. (2008). The Hybrid network consists static and mobile sensor nodes in the network. The authors defined a term over-provisioning factor, which is the ratio of the sum of densities of static and mobile sensor nodes to a constant k. Here k is desired level of coverage in the FoI. The proposed work used the kinematics of flow, *i.e.*, the excess flow of nodes recursively moves to the lower height nodes or low density region. The algorithm initially divides the whole network area into equal size of square cells. Then, mobile and static sensor nodes in the same cell i communicate with each other to compute the required static sensor nodes n_i, mobile sensor nodes m_i, and vacancies $v_i = [k - n_i]^+$ for k-coverage of the FoI. A sensor node works as a coordinator of the cell that stores the necessary information during the algorithm execution. A cell consists input and output vertices and height of vertices in neighboring cells. The cell used the push-relabel algorithm and estimates the movement of the mobile sensor nodes from the current cell to neighbor cell. Such movement depends on the in-flow and out-flow of the cells. Let L be the side length of a square shaped FoI. We summarize the main results of this chapter as follows: (i) The static sensor node density should increase as $O(k\,log\,log\,L + log\,L)$ for k-coverage of the FoI, (ii) In all-mobile sensor networks, sensor density should increase as $O(k)$ and the maximum distance for the mobile sensor nodes is $O(\frac{1}{\sqrt{k}} log^{\frac{3}{4}}(kL))$ to provide k-coverage, (iii) this hybrid network structure consists of $O(k)$ static sensor density, $O(\sqrt{k})$ mobile sensor density, and maximum distance of the mobile sensor nodes is $O(log^{\frac{3}{4}}(L))$ to provide k-coverage.

Some monitoring applications of WSNs consist hard-deadline, where the event must be detected in the given deadline. Such hard-deadline is known as Maximum Allowable Response (MAR) time in the literature Gupta et al. (2017). The authors in Gupta et al. (2017) assumed that the mobile sensor nodes are moving in a given three-dimensional FoI. The volume of the FoI is $lenght(l) \times width(b) \times height(h)$. The main objective of the work is to calculate the critical sensor density of mobile sensor nodes in the FoI, so that a randomly generated event must be in the sensing range of atleast one sensor node in the given MAR time. The work in this chapter considered the border effects.

2.5 Coverage and Connectivity (CaC) in WSNs

Previous section reviewed the existing work that focuses mainly on monitoring of the events in the given region. The communication of the sensory data from sensor nodes to the sink is also an important issue of the research in WSNs Haider et al. (2015); Liu et al. (2017); Sarigiannidis et al. (2017). In this section, we review the existing work that

Table 2.2 Illustration of the probabilistic approaches for solving the coverage problems in WSNs.

Issue/ Paper	Deployment of Sensors		Node Type		Mobility of Nodes		FoI Dimension		Solution Approach		Fault Tolerant	Connectivity	Energy Efficient	Border Effect
	Random	Deterministic	Homogeneous	Hetrogeneous	Static	Mobile	2-D	3-D	Centralized	Distributed	k-Coverage			
So and Ye (2005)	√		√		√		√	√	√		√			√
Carbunar et al. (2004)	√		√		√		√			√				
Carbunar et al. (2006)	√		√	√	√		√			√	√		√	√
Ghosh (2004)	√		√		√		√			√				
Ghosh and Das (2005)	√		√		√	√	√			√		√		
Jiang et al. (2005)	√		√		√		√		√			√		
Boukerche and Fei (2007)	√		√		√		√			√				
Wang et al. (2006)	√		√			√	√			√				
Alam and Haas (2006)	√	√	√		√		√	√						
Zhang (2012)	√		√		√		√			√				
Stergiopoulos et al. (2012)	√		√		√	√	√			√				
Habibi et al. (2017)	√		√	√		√	√			√				
Qiu et al. (2017)	√					√	√			√	√			
Kim et al. (2017)	√			√	√		√			√			√	
Han et al. (2017)	√			√	√				√			√	√	
Kim et al. (2017)	√		√			√	√		√				√	
Alia and Al-Ajouri (2017)		√	√		√		√			√			√	
Al-Karaki and Gawanmeh (2017)	√		√		√		√		√			√		
Chatterjee et al. (2017)	√		√		√		√		√					
Gao et al. (2017)	√		√			√	√		√				√	
Khan et al. (2017)	√		√			√		√						
Cheng and Wang (2017a)	√		√		√		√		√					
Zhuang et al. (2017)	√		√		√		√		√					
Gupta et al. (2017)	√			√		√		√	√		√			
Cheng and Wang (2017b)	√		√		√		√	√						
Elhoseny et al. (2017)	√		√		√		√		√		√		√	
Khalifa et al. (2017)	√		√		√		√		√					
Han et al. (2016)	√		√		√		√		√				√	
Rout and Roy (2016b)	√		√			√	√			√				
Rout and Roy (2016a)	√		√			√	√			√			√	
Guo et al. (2016)		√	√		√		√		√					
Gupta et al. (2016b)	√			√	√		√		√		√			
Misra et al. (2016)	√		√		√		√		√					
Wang et al. (2016a)	√		√		√		√		√					
Cho et al. (2016)	√		√			√		√	√					
Wang et al. (2016b)	√		√		√		√		√					
Latif et al. (2016)	√		√		√			√	√					
Zhang et al. (2016b)	√		√		√		√		√		√		√	
Gupta and Rao (2016)	√			√	√		√					√	√	
Kilinc et al. (2015)	√		√		√		√		√			√		

are used to solve the Coverage and Connectivity (CaC) problem in WSNs. Table 2.3 illustrates the existing work of solving the CaC problem in WSNs.

2.5.1 Maximizing Network Lifetime

An integrated Coverage and Connectivity configuration Protocol (CCP) is proposed by Wang *et al.* Xing et al. (2005). The protocol provides the k level of monitoring of the FoI with k connectivity in the network, where $k \geq 1$. The protocol can be changed the level of monitoring based on the requirement of the applications in connected WSNs. The main objective of this work is to prolong the lifetime of a connected WSN. The proposed method for estimating the redundancy of a sensor node checked whether the intersection point of the parameter of the sensing region are covered or not. A sensor node is a redundant sensor node if all intersection points of the parameter is covered by neighbor sensor nodes. A scheduling mechanism is used in the protocol to activate sensor nodes. Initially, all sensor nodes in the network remain in OFF state. Each sensor node executes an algorithm named as *eligibility algorithm*, to decide if it should go to ON state, or to stay back in OFF state. The authors proved that if the transmission range is at least two times the sensing range of a sensor node then coverage verification is sufficient for connectivity.

Most of the proposed solutions for solving the CaC problem work only for homogeneous WSNs. The heterogeneity is also an important issue in designing of a WSN. The authors in Gupta et al. (2013) considered heterogeneous WSNs for partial coverage of the FoI. In such application, some region of the FoI is required to be monitored by the deployed different types of sensor nodes. Here, sensor nodes can be classified based on the sensing and communication radii. The authors estimated the redundancy of the sensor nodes and turned them sleep state for reducing the energy consumption of the heterogeneous WSNs. The proposed work shown that a sensor node is a redundant sensor node if the redundancy degree of the sensor node is greater than the coverage ratio of the FoI. The work considered the listen state for handling the black hole in the FoI, *i.e.*, to remove the scenario where two neighbor redundant sensor nodes simultaneously try to switch in sleep state.

A distributed and localized algorithm is known as Optimal Geographic Density Control (OGDC) is proposed by Zhang *et al.* Zhang and Hou ([n. d.]) for maximizing the number of sleeping sensor nodes while ensuring that each event must be monitored in a connected WSN. OGDC algorithm considered the following design issues: monitoring of the FoI, connectivity in the network, and prolong the lifetime of the network. The work has shown that a sensor network that covered a FoI must be connected if sensing range is less than the half of the communication range Zhang and Hou ([n. d.]). The parameter of sensor nodes divided into a grid and check whether the centre point of the grid is covered or not. A sensor node is redundant and eligible for sleeping if the grid points are covered by its neighbor sensor nodes. Each time when a sensor node hears a power-on message, it updates the bitmap. The sensor checks whether its grid points are covered or not. The sensor nodes change the state from sleep to active or still in sleep state.

Complete coverage of the FoI assumes that each event in the FoI is monitored by at least one sensor node. Some applications of WSNs do not require complete coverage of the FoI. Example of such applications is environmental information monitoring, forest temperature monitoring, or river water level monitoring, where each point of the FoI is not required to monitor. Such applications require partial coverage of the given region where the coverage ratio of the FoI is less than unity. Gupta and Rao (2016) presented a Demand-Based Coverage and Connectivity-preserving Routing (DBCCR) protocol for maintaining the required level of monitoring of the FoI in a connected WSN. A sensor node changes ON and OFF states based on the requirement of the users. The protocol uses relay sensor nodes based technique, known as local route optimization with power control, for reducing the energy consumption during transmission of sensory data. The proposed work does not require any central control or location information of sensor nodes for maintaining the coverage of the FoI in a connected WSN.

2.5.2 Critical Sensor Density of Sensor Nodes

The authors in Ammari and Das (2010); Aslam and Robertson (2010); Cardei and Wu (2006); Gupta et al. (2003, 2014); Huang and Tseng (2005); Huang et al. (2007); Li and Gao (2008); Wan and Yi (2006); Zhou et al. (2004) proposed the methods to estimate the critical sensor density of sensor nodes for solving CaC problem in omni-dimensional WSNs. The authors in Gupta et al. (2016a) solved the CaC problem for directional WSNs.

A directional WSN consists of the sensor nodes whose sensing region is bounded in a given direction. The directional sensor node cannot be detected the targets in other directions, even the distance between the target and the sensor node in not more than the sensing range of the sensor node. The authors in Gupta et al. (2016a) considered a three-dimensional WSN scenario where the directional sensor nodes (*e.g.*, camera sensor) are randomly deployed in a given three-dimensional FoI. The sensing region of such sensor nodes is a three-dimensional sector. The proposed work considered the following issues: heterogeneity in sensing and communication regions, fault-tolerant sensor nodes, k-coverage of the FoI, and m-connectivity of the network. The authors presented the analysis for desired level of coverage and connectivity in directional three-dimensional WSNs. The authors used the analysis and presented a minimum cost network algorithm for fault-tolerant WSNs.

Gupta *et al.* Gupta et al. (2003) proposed an algorithm that selects minimum number already connected sensor nodes for coverage of the FoI. The algorithm iteratively selects a path of sensor nodes that are connected to an already selected sensor node until the region is not covered. Zhou *et al.* Zhou et al. (2004) solved the CaC problem as monitoring and m-connectivity problem. An energy-efficient approach which employs adjustable sensing range at each sensor node is proposed by Cardei and Wu Cardei and Wu (2006). The authors used linear programming and greedy techniques for solving the CaC problem.

Huang and Tseng Huang and Tseng (2005) used the term parameter coverage to verify the coverage of the FoI. The authors proved that each point in the FoI is covered by k sensor nodes only if the parameter of a randomly selected sensor node is overlapped by k sensor nodes. Fig. 2.4 shows that the sensor node s_1 is candidate for its three direct neighbors. Further, Huang *et al.* Huang et al. (2007) extended the k-perimeter-coverage method and developed the decentralized energy efficient solution for determining the level of coverage and connectivity of WSNs, by putting some sensor nodes in sleep mode and turning their communication radio in OFF state. The main limitation of this work is that it is applicable only if the location of all sensor nodes are different.

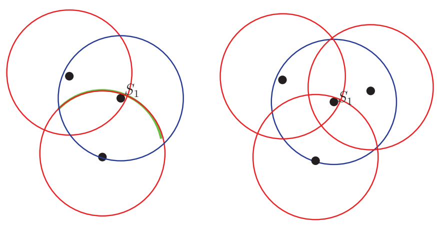

Figure 2.4 Perimeter coverage for redundancy check.

Table 2.3 Illustration of Coverage and Connectivity (CaC) problems in WSNs.

Issue/ Paper	Deployment of Sensors		Node Type		Mobility of Nodes		FoI Dimension		Solution Approach		Fault Tolerant k-Coverage	Connectivity	Energy Efficient	Border Effect
	Ran-dom	Deter-ministic	Homo-geneous	Hetro-geneous	Static	Mobile	2-D	3-D	Centralized	Distributed				
So and Ye (2005)	√		√		√		√	√	√		√			√
Carbunar et al. (2004)	√		√		√		√			√				
Carbunar et al. (2006)	√		√	√	√		√			√	√		√	√
Ghosh (2004)	√		√		√		√			√				
Ghosh and Das (2005)	√		√		√	√	√			√		√		
Jiang et al. (2005)	√		√		√		√		√			√		
Boukerche and Fei (2007)	√		√		√		√			√				
Wang et al. (2006)	√		√			√	√			√				
Yang and Chin (2017)	√		√		√	√	√			√		√	√	
Wei et al. (2017)	√		√		√		√				√	√	√	
Han et al. (2017)	√			√	√				√			√	√	
Al-Karaki and Gawanmeh (2017)	√		√		√		√		√			√		
Khalifa et al. (2017)	√		√		√		√		√					
Gupta et al. (2016b)	√			√	√		√		√		√			
Cho et al. (2016)	√		√			√		√	√					
Bao et al. (2016)	√		√		√		√		√			√		

Yingshu and shan Li and Gao (2008) investigated two new heuristic approaches named as greedy-selection and greedy-selection-adjustable for providing k-joint and disjoint cover sets of a FoI and reducing the energy consumption of WSNs. The main idea behind this work is to recursively create the sensor node sets by selecting the sensor nodes from lowest sensor density. Habib and Das Ammari and Das (2010) developed a new method to solve the Minimum Connected k-Coverage (MCC) problem. The proposed method can be divided into the following two parts: divide the sensing region and non-redundant sensor node scheduling. In the divide the sensing region, a sensor node is decomposed into equal size subregions. The sensing region of a sensor node is divided into six and twelve subregions in two-dimensional and three-dimensional WSNs, respectively. The authors proved that a sensor node is redundant for k coverage of the FoI only if each subregion consists atleast k sensor nodes. In the non-redundant sensor node scheduling part, each sensor node checks whether it is redundant or not. If a sensor is redundant then change its state into sleep state else stay in active state. The authors proposed centralized and distributed sleep scheduling protocols without any location information of sensor nodes. A local information based distributed algorithm for full coverage of the FoI is proposed by Nauman and WilliamAslam and Robertson (2010). The idea of this work is to select a minimum number of sensor nodes such that the selected nodes are sufficient for coverage of the FoI.

2.5.3 Outside Deployment of Sensor Nodes

Due to small size, fast memory, long battery lifetime, and other advancement in sensor nodes, the WSNs find their applications in different scenarios. As we have seen in this survey chapter, most of the scenarios are required that the sensor nodes are monitored the deployed region. However, some scenarios are required that the sensor nodes are monitored outside the deployed region. Example of such scenarios are water surface monitoring, transport monitoring, or region border monitoring. In such application scenarios of WSNs, the sensor nodes are randomly or deterministic deployed outside the region for monitoring the region that is nearby the deployed region. The authors in Gupta et al. (2015a) considered the scenario where sensor nodes are monitored the nearby region of the deployed region

2.5.4 Regular Deployment of Sensor Nodes for CaC Problem

As we have discussed that the deployment of sensor nodes can be classified into random and deterministic methods. The random deployed of sensor nodes takes less time to deploy the WSNs in the FoI. However, the random deployment requires a large number of sensor nodes as compared with deterministic deployment for the same level of coverage of the given region and connectivity in WSNs. The authors in Gupta et al. (2015b) illustrate the advantages of deterministic deployment of sensor nodes in a given region. The authors used three possible regular deployment patterns, *i.e.*, triangle, hexagon, and square. The proposed work is suitable for different level of coverage and connectivity in the WSNs.

2.6 Conclusion

This chapter presents the existing work on monitoring the FoI and connectivity in WSNs. Based on the requirement of monitoring of the targets, coverage can be classified into area coverage, point coverage, and barrier coverage. We mainly focused on area coverage of the FoI in this work. The research work for estimating the sensing coverage in the FoI using the deployed sensor nodes in WSNs has been studied and summarized. We described issues and challenges for designing the coverage and connectivity preserving computation geometry and probabilistic based approaches. We considered the essential design issues such as type of sensor nodes, deployment region, shape of the FoI, and border effects. In addition to that impact of sensing models binary and probabilistic for sensing the FoI has been objectively discussed. Table 2.4 summarizes some selected problem statements and existing solutions that we have discussed in this chapter.

The survey shows that most research work assumed that the sensor nodes are deployed in two-dimensional WSNs, homogeneous sensor nodes, and the infinity boundary of FoI for avoiding border effects. However, the practical applications scenarios of WSNs require that the sensor nodes are deployed in three-dimensional FoI, heterogeneous sensor nodes, and fixed size FoI. The gap between the existing work and practical applications requirements needs to be addressed in future research.

Table 2.4: Summary of some important literature survey.

Paper	**Problem Statement**	**Proposed Solution**
Alam and Haas (2006)	What is the best way to place the sensor nodes in a wireless sensor network such that the number of nodes required for surveillance of a 3D FoI is minimized?	Proposed a Kelvins conjecture-based placement strategy that places sensor nodes in the middle of truncated octahedral cells, created by the Voronoi tessellation of a 3D space.
Aslam and Robertson (2010)	How to find an optimal set of sensor nodes that can cover the 3D FoI efficiently while maintaining the network connectivity?	Proposed a distributed algorithm that allows sensor nodes to form a 1-covered topology by exchanging local information based messages.
Carbunar et al. (2006)	How to detect and eliminate redundancy in a WSN with a view to improving energy efficiency, while preserving the coverage?	Presented a Voronoi diagram-based distributed algorithm for the coverage-preserving, energy-efficient redundancy elimination problem.
Ghosh (2004)	What is the size of coverage holes in the sensing region and how many numbers of additional mobile nodes that needs to be deployed and relocated to reduce or eliminate coverage holes?	Presented a method to estimate the exact amount of holes using Voronoi diagrams and the number of additional mobile nodes needed to be deployed, and relocated to optimal positions to maximize coverage.
Chellappan et al. (2007a)	How to determine an optimal movement plan for the sensor nodes in order to maximize the coverage and simultaneously minimize the total number of sensor movements?	Proposed a minimum-cost maximum-flow-based solution that is executed by the base-station to determine the movement plan. The base-station will then forward the movement plan to corresponding sensor nodes.
Gupta et al. (2003)	How to reduce the communication cost of a query in connected WSNs?	Developed the notion of a connected sensor cover and design a centralized approximation algorithm that constructs a topology involving a near-optimal connected sensor cover.
Ammari and Das (2010)	What is the critical sensor density required for k-Coverage in a connected 3D WSNs?	Proposed a Reuleaux tetrahedron model for solving the problem.
Chakrabarty et al. (2002)	How to deploy the sensor nodes in a grid pattern for a full coverage in minimum cost WSNs?	Presented an integer linear programming solution for minimizing the cost of sensor nodes for complete coverage of the sensor field.

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Paper	**Problem Statement**	**Proposed Solution**
Cardei et al. (2005)	How to design a mechanism that allows redundant sensor nodes to enter the sleep mode for target coverage?	Designed two heuristics that efficiently compute the non-disjoint sets, using linear programming and a greedy approach.
Huang et al. (2007)	How to determine the levels of coverage and connectivity of WSNs with an arbitrary relationship between sensing and communication ranges?	Developed decentralized solutions for determining, or even adjusting, the levels of coverage and connectivity of a given network.
Zhang and Hou (2004)	What is the necessary and sufficient condition of the sensor node density in order to maintain complete k-coverage with probability approaching to unity? What is the upper bounds of lifetime when only α-portion of the FoI is covered by a given node density.	Derived the asymptotic sensor node density required to ensure full coverage for the duration of k times the lifetime of a single sensor. Also derived two upper bounds of α-lifetime in a finite region with a finite density of nodes.
Kumar et al. (2004)	What is the relation between among number of sensor nodes (n), sensing range (r), and active with probability (p) would be sufficient to guarantee that the probability of the entire FoI being (not) k-covered approaches 1 as n approaches infinity?	Considered deterministic, random uniform, and Poisson deployments for a sensor network. Claimed that the critical value of the function $np\pi r^2/log(np)$ is 1 for the event of k-coverage of every point.
Ke et al. (2007)	Given sensing and communication ranges, a FoI divided into grids, and a set of critical grids, does a WSN exist that fully k-covered all critical grids by deploying no more than k sensor nodes on grid points?	Proved that deployingsensor nodes on grid points to construct WSNs that fully covers critical grids using minimum sensor nodes and a maximum total weight of grids using a given number of sensor nodes problems are each NP-Complete.
Kumagai (2004)	How to use complete coverage algorithm for solving the partial coverage problem?	Proposed a framework for solving partial coverage problem using complete coverage algorithm with any coverage ratio by running a complete coverage algorithm to find full coverage sets with virtual radii and converting the coverage sets to partial coverage sets via adjusting sensing radii.
Wang et al. (2006)	How to estimate the correct places of mobile sensor nodes tIllustration of the selected problem statements and existing solutions.o provide the required coverage?	Using Voronoi diagrams, designed two sets of distributed protocols for controlling the movement of sensor nodes, one favoring communication and one favoring movement.

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Table 2.4 – *Continued from previous page*

Paper	**Problem Statement**	**Proposed Solution**
Wang et al. (2008)	What is the maximum distance that a mobile sensor will have to move in all-mobile sensor networks and hybrid sensor networks for k-coverage WSNs?	Proposed a hybrid network structure, proved that k-coverage is also achievable with a constant sensor density of $O(k)$, and proposed a distributed relocation algorithm, where each mobile sensor only requires local information in order to optimally relocate itself.
Xing et al. (2005)	What is the relationship between sensing coverage and network connectivity for k-coverage in connected WSNs.	Proved that the sensing k-coverage always implies network connectivity if sensing range is at least twice that of communication range.
Zhang and Hou (2006)	How many sensor nodes are required to achieve a certain level of coverage under Poisson point process, uniformly randomly, and regular grids deployment strategies?	Proved that that under most circumstances, grid deployment renders asymptotically lower node density than random deployment. These results override a previous conclusion that grid deployment may render higher node density than random node distributions.
Bai et al. (2009)	What is the optimal way to deploy sensor nodes in a 3D space such that the number of required nodes is minimized, the volume is fully covered, and there exist k-connectivity?	Designed a set of patterns for 14- and 6- connectivity and full coverage, and proved their optimality under any values of the ration of communication and sensing range, among regular lattice patterns.
Ammari and Das (2009)	What is the critical density required for coverage and connectivity in 3D WSNs using Continuum Percolation?	Proposed an integrated-concentric-sphere model to address coverage and connectivity in 3D WSNs in an integrated way. Computed the critical density above which coverage percolation, connectivity percolation, and both coverage and connectivity percolation in 3D WSNs will almost surely occur.
Ravelomanana (2004)	Given n sensor nodes of sensing range R_s are randomly and uniformly distributed in a 3D FoI of volume V, how large must the sensing range R_{max} to ensure a given degree of coverage of the region to monitor?	Investigated and analyzed the network topology according to the region of deployment, the number of deployed sensor nodes, and their transmitting/sensing ranges.

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Paper	**Problem Statement**	**Proposed Solution**
Zhang et al. (2010)	What is the optimal way to deploy sensor nodes such that the number of required nodes is minimized, the network is 1-, 2-, 3- and 4-connected and full-coverage?	Designed a set of patterns to achieve desired connectivity and coveragIllustration of the selected problem statements and existing solutions.e, and proved their optimality under any value of the ratio of communication range over sensing range, among regular lattice deployment patterns.
Jin et al. (2009)	What is the critical sensor density required for k-coverage and m-connectivity in a heterogeneous WSN under border effects?	Proposed the analysis for estimation of critical sensor density when sensor nodes are randomly deployed in a circular shaped FoI. Using this analysis they proposed a location-independent, energy-efficient routing algorithm.
Weng et al. (2018)	How to design disjoint sets of sensor nodes such that each set of sensor nodes satisfies the k-barrier coverage?	Proposed decentralized barrier construction algorithms, named best-fit coverage approach and top-down one-coverage barrier approach, aiming to explore the maximal number of disjoint sets.
Yang and Chin (2017)	What are the feasible locations to place the minimal number of sensor nodes used for sensing and relaying such that deployed sensor nodes cover all targets, have a path to the sink, and have energy neutral operation?	Proposed a mixed integer linear program-based approach, whereby a greedy heuristic is used to generate a collection of locations. Also proposed direct search and greedy search heuristics.
Wei et al. (2017)	How to schedule the low residual energy sensor nodes in an inactive state for prolong the network lifetime?	Presented an energy balance and coverage control algorithm for the overlay network model based on sensor node position relations.
Gupta et al. (2016b)	How to select redundant sensor nodes for k-coverage in a 3D heterogeneous WSN without the location information?	Proposed a probabilistic technique to identify the sensor nodes redundant. Using this analysis they proposed a distributed scheduling protocol that does not require geographical information, to schedule the redundant sensor nodes to sleep without creating holes in the coverage.
Gupta et al. (2017)	How many sensor nodes are required for coverage of a 3D FoI using mobile WSNs with a given sampling rate of the sensors?	Proposed the analysis for estimating the critic sense density for k-coverage using straight line mobility model. Due to border-effect, used the effective sensing range instead of sensing range, in the proposed analysis.

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Paper	**Problem Statement**	**Proposed Solution**
Gupta et al. (2016a)	What is the critical sensor density required for k-coverage and m-connectivity in a heterogeneous 3D WSN?	Proposed the analysis for estimating the critical sensor densities for the desired coverage and connectivity. Also used the analysis for designing the minimum cost heterogeneous 3D WSNs, where sensing and communication radii of all sensor nodes are not equal.
Zhang et al. (2017b)	How to obtain a better trade-off among the following objectives to minimize: total power consumption while satisfying full coverage; 2) the number of active sensor nodes to improve the reliability; and the active sensor nodes maximum sensing range to maintain fairness?	Presented a multiobjective optimization framework based on multiobjective evolutionary algorithm. Incorporated problem-specific knowledge into local search, which allows search procedures for neighboring subproblems collaborate each other.
Han et al. (2017)	How to select an existing coverage and connectivity strategy for an industrial application?	Analyzed characteristics of recent energy-efficient coverage strategies by carefully choosing four representatives connected coverage algorithms. Through a detailed comparison in terms of network lifetime, coverage time, average energy consumption, ratio of dead nodes, etc., characteristics of basic design ideas used to optimize coverage and network connectivity of IWSNs are embodied.
Kim et al. (2017)	How to organize hybrid sensor network, which consists of a number of energy-scarce ground sensors with homogeneous initial battery level and energy-plentiful mobile sensor nodes, to maximum the lifetime of barrier-coverage?	Proposed a simple heuristic algorithm by combining existing ideas along with our own and designed an efficient algorithm for the problem and proved that the lifetime of hybrid barrier constructed by this algorithm is at least three times greater than the existing one on average.
Yu et al. (2017)	How to select a minimum subset of sensor nodes among the randomly deployed ones such that each point in the target FoI is covered by at least k sensor nodes?	Proposed centralized and distributed protocols based on the novel concept of Coverage Contribution Area, which helps to get a lower sensor spatial density. The protocols take the residual energies of the sensor nodes into consideration.

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Paper	**Problem Statement**	**Proposed Solution**
Deng et al. (2017)	How to solve Confident Information Coverage (CIC) hole healing problem, where the goal is to select some randomly scattered mobile nodes to be dispatched to the CIC holes detected by the stationary nodes such that the CIC holes can be repaired and the confident information coverage performance can be satisfied?	Proposed two heuristic solutions where the main aim is to efficiently healing the CIC holes while minimizing the total moving energy consumption, or maximizing the mobile nodes' average remaining energy after movement, or minimizing the maximum mobile energy consumption of each dispatched mobile node.
Mahboubi and Aghdam (2017)	How to compute new candidate position of each mobile sensor with the following goal: when the sensor is relocated, the covered area of the corresponding region increases?	Proposed the algorithms for computing the position of sensor nodes based on the multiplicatively weighted Voronoi diagram. Here, each sensor is driven by some virtual forces which are applied to it from the vertices and boundaries of its Voronoi cell.
Chatterjee et al. (2017)	How to deploy the sensor nodes in the FoI such that they generate minimum traffic, just sufficient for coverage?	A distributed, nearly load-balanced data gathering algorithm developed to deliver packets to the sink node via minimum-hop paths that also in turn helps to limit the network traffic.
Gao et al. (2017)	How to schedule mobile sensor nodes and minimize their moving distance, while keeping the target coverage requirement?	Proposed centralized and distributed polynomial-time approximation schemes with the goal is to minimize the moving distance of sensor nodes to cover all targets in the surveillance region, which is in Euclidean space.
Qiu et al. (2017)	How to solve k-coverage problem using distributed Voronoi cells in mobile WSNs.	Proposed distributed Voronoi based cooperation scheme that enables nodes to monitor others' critical points around themselves by building. The scheme constrains the movement of every node to avoid generating new holes.