Chapter 1
Overview of Wireless Sensor Networks

This chapter gives a brief introduction to wireless sensor networks (WSNs) and presents the major challenging problems in their design. Moreover, it describes a sample of their potential applications as well as a key set of design requirements of the protocols proposed in this book. Furthermore, it states the problems being investigated in this book along with a brief description of their solutions.

1.1 Introduction

Recent advances in miniaturization, low-cost and low-power circuit design, and wireless communications have led to the development of low-cost, low-power, and tiny communication devices, called sensors. Like nodes (or computers, laptops, etc.) in traditional wireless networks, such as mobile ad hoc networks, the sensors have data storage, processing, and communication capabilities. Unlike those nodes, the sensors have an extra functionality related to their sensing capability. However, the sensors suffer from severe limitations of several resources and capabilities, such as battery power (or energy), storage, processing, sensing, and communication, compared to personal computers, for instance, with energy being the most crucial one. For an excellent survey on sensor networks, the interested reader is referred to [6, 7].

A wireless sensor network is composed of a large number of sensors that are densely deployed in a field of interest to monitor specific phenomena. The sensors can be engaged in a variety of sensing tasks, such as temperature, sound, vibration, light, humidity, etc. These sensors sense specific environment phenomenon and perform in-network processing on the sensed data before sending their results to a central gathering node, called the sink. In this type of network, sensors communicate with each other (possibly) through multi-hop wireless communication links and forward sensed data on behalf of others so the sink can receive them on-time for further processing and analysis. WSNs can be used for a wide variety of applications dealing with monitoring (health environments monitoring, seism monitoring, etc), control (object detection and tracking), and surveillance (battlefields surveillance).

Compared to traditional wireless networks, such as mobile ad hoc wireless networks, WSNs have several inherent characteristics. First, the sensors are very tiny and hence more susceptible to hardware failure. It is worth mentioning that battery power (or energy) is the most crucial resource, and hence sensors can also fail due to low energy. Second, the sensors are deployed in a field with high density to extend the network lifetime. Indeed, using a large number of sensors
facilitates multi-hop communication between them, and hence the sensors can save their energy by transmitting or forwarding their sensed data through short distances. Third, the network topology may change very frequently as sensors join and/or leave the network. Thus, protocols designed for WSNs should account for all these features, which are inherent to these types of networks so they remain operational as long as possible.

The remainder of this chapter is organized as follows. Section 1.2 gives the challenges that face the design of WSNs while Sect. 1.3 describes a sample of their potential applications. Section 1.4 presents the motivations of the work in this book. Section 1.5 describes the major requirements driving the design of the protocols that we propose in this book. Section 1.6 discusses the major contributions of this book by stating the main problems that are addressed in this book along with a brief overview of the proposed solutions. Section 1.7 summarizes this chapter.

1.2 Major Challenges

The design of network protocols for WSNs, including those for coverage configuration and data dissemination, is a challenging problem due to several constraints. Next, we describe these constraints that are imposed not only by the characteristics of the individual sensors, the behaviour of the network, and the nature of physical environments (or deployment fields) but also by the requirements of the sensing applications in terms of some desirable metrics.

1.2.1 Limited Resources and Capabilities

Because of their inherent characteristics, the design of WSNs for different applications running in different deployment fields is facing several challenges. First of all, energy efficiency is the primary concern in the design of WSNs. Indeed, the sensors forming a network suffer from the limitations of several resources, such as storage, CPU, bandwidth, communication, sensing, and battery power (or energy). In particular, energy is the most crucial resource as it determines the lifetime of the sensors and hence the lifetime of the entire network. Energy poses a serious problem for network designers especially in hostile environments, such as battlefields, where it is difficult or even impossible to access the sensors and recharge or renew their batteries. Furthermore, when the energy of the sensors reaches a certain threshold, they become unreliable (or faulty) and would not be able to function properly. As a consequence, the behaviour of those faulty sensors will have a major impact on the network performance. Thus, network protocols and algorithms designed to be run by the sensors should be as energy efficient as possible to extend their lifetime and hence prolong the network lifetime while guaranteeing good performance overall.
1.2 Major Challenges

1.2.2 Location Management

Sensor location management is another major challenge in the design of deployment strategies to achieve a certain degree of coverage. In most of the protocols designed for WSNs, the sensors are aware of their locations through either the use of global positioning system (GPS) receivers or some localization technique, such as the ones proposed by Bulusu et al. [52] and Ji and Zha [114]. On one hand, a GPS receiver-based solution provides the sensors with highly accurate locations but is not cost-effective for densely deployed sensors given that each sensor should be equipped with a GPS receiver. On the other hand, the use of a localization technique does not require any additional cost but may not guarantee high sensor location accuracy.

1.2.3 Sensor Deployment

As mentioned earlier, a deployment field may cause a problem not only to access the sensors for replacing and/or recharging their batteries but also for their deployment. Thus, a deterministic sensor deployment strategy is not always possible. Such a strategy would help cover the field appropriately and minimize the total number of sensors required to achieve the specific needs of sensing applications in terms of their expected type of coverage. Indeed, an application may demand partial coverage where only a certain percentage of the field is covered; full coverage, where the entire field is covered; or redundant coverage, where every location in the field is covered by multiple sensors simultaneously. In the case where the sensors cannot be deployed deterministically because of the field nature, random deployment is the only remaining strategy. However, there is no guarantee that the coverage required by the application would be satisfied. There might be some areas that are not covered well or even not covered at all and this would lead to a problem, known as coverage hole. Moreover, all the deployed sensors are not guaranteed to be connected to each other or to the sink. This would lead to another problem, known as connectivity hole. These are two of the reasons why most of time WSNs are designed with densely deployed sensors. Thus, the nature of the field has an influence on the network and this is a challenge for the designer and the investing party at least cost-wise. As will be discussed later, one of the most widely used assumption in the design of routing and data dissemination protocol is highly sensor density. Although highly dense deployed WSNs involve more than necessary sensors, they help guarantee network connectivity and achieve the coverage demanded by the application.

1.2.4 Time-Varying Network Characteristics

The topology of a wireless sensor network, which is defined by the sensors and communication links between them, changes frequently due to sensor addition and deletion. When new sensors decide to join the network, the neighbour sets of some sensors have to be updated. Indeed, it may seem necessary to add more sensors to
maintain certain properties of coverage of the deployment field and network connectivity. Similarly, when the sensors deplete all their energy, they are considered faulty and no longer belong to the network. Thus, the neighbour sets of the fault sensors’ neighbours should be updated. Also, in mobile WSNs, the network topology gets updated as the sensors move in the deployment field. Consequently, any topology change in the network will have an impact on the communication paths (or routes) between the sensors in the network. Therefore, routing and data dissemination paths should consider network topology dynamics due to limited energy and mobility of the sensors as well as increasing the size of the network to maintain specific application needs in terms of coverage and connectivity. It is worth noting that connectivity to the sink is very important. In fact, coverage would be meaningless if the sensed data cannot reach the sink, i.e., there is no communication paths between the source sensors (or data generators) and the sink. Thus, connectivity between all source sensors and the sink either directly or indirectly should be guaranteed for the correct operation of the network.

1.2.5 Network Scalability, Heterogeneity, and Mobility

The design of protocols for connected \( k \)-covered WSNs should consider network scalability. In other words, these protocols should scale with the number of sensors in the network, sensor mobility, and the size of the deployment field. For large-size networks, the number of sensors could be on the order of thousands. Also, the sensors may not necessarily be static given that sensor mobility helps achieve better quality of coverage [76, 144]. Furthermore, the sensors could be heterogeneous with regard to their storage, processing, communication, sensing, and energy capabilities and resources. In real-world applications, WSNs are composed of heterogeneous sensors that have a potential to increase the network lifetime and reliability without causing significant increase in its cost [209]. Indeed, deploying heterogeneous sensors reduces the probability of simultaneous failure of the entire neighbour set of a sensor [13].

1.2.6 Sensing Application Requirements

In most sensing applications, the sensed data should be as accurate as possible to assure better decision making by the sink. Moreover, the sensed data needs to reach the sink in a timely manner. Thus, the delay metric should also be considered in the design process of WSNs; otherwise, the underlying network may not be useful. Also, for several sensing applications, data redundancy is desirable in that it increases data accuracy. For instance, in an intruder detection and tracking application, multiple sensors should be active at the same time to gather enough information about the intruder and track its motion accurately. Therefore, the design of coverage configuration and routing and data dissemination protocols should guarantee data delivery and accuracy so the sink can gather the required knowledge about the physical phenomenon on time. Furthermore, the sensors may
deplete their energy before expected and become faulty. As discussed earlier, a deployment field may not be accessible and thus replacing those faulty sensors would be impossible. Hence, a wireless sensor network should tolerate the presence of faulty sensors and remain functional in spite of those failures. The degree of fault tolerance of a network depends on the underlying sensing application. Thus, coverage configuration and routing and data dissemination protocols for WSNs should be fault tolerant for this type of sensor failure. It is worth noting that the link and sensing unit failures may also occur during the operation of a wireless sensor network. While sensing unit failure are due to imperfections in manufacturing or aging, link failures are caused by sensor failures and sensor mobility. In this book, however, we only consider sensor failures due to low battery.

1.3 Sample Sensing Applications

The design of WSNs should also be guided by the very specific requirements of the target applications. The knowledge gathered about the underlying application would help a network designer deploy more appropriate types of sensors and develop algorithms and protocols that meet the needs of the application. In this section, we describe some potential applications of WSNs spanning health, home, environmental, and military areas [6, 7].

- **Tracking and monitoring a hospital**: Sensors may be attached to patients and doctors. For a patient, specific sensors are used to perform a particular task. For instance, to detect the heart rate, a special sensor needs to be used. Also, to detect the blood pressure, another specific type of sensor has to be used. For a doctor, sensors may be used to track their locations in the hospital to facilitate their mission.

- **Smart environment**: One of the home applications is the design and development of a smart home (or environment), where a wireless sensor network can be deployed to satisfy the specific needs of habitants. The sensors could be embedded anywhere in a room (or apartment) and communicate with each other to offer services desired by habitants. For instance, for saving energy, the light and temperature in a room could be controlled by the sensors. In this case, the light is on only when the habitants are in the room and the temperature should be set to appropriate value depending on the time and season, for instance. The goal of this type of network is to provide habitants with the level of comfort they wish to have without any human intervention.

- **Forest fire detection**: The sensors could be randomly and densely deployed in a forest to detect the origin of a fire and report this information in a timely fashion to the end users to act accordingly before the fire spreads. This helps avoid catastrophic situations that may result. In this type of application, the sensors may be used for a long period of time, and hence have to be equipped with continuous source of energy, such as solar cells. Furthermore, the sensors need to collaborate with each other in their
sensing activity to overcome several problems, such as obstacles. Also, the sensors should be densely deployed for a quick and accurate detection.

- **Intruder detection and tracking**: Business stores, for instance, could be covered with special sensors to detect and track the motion of intruders. To achieve high accuracy of detection and tracking of an intruder, sensor redundancy is desirable and hence a dense network should be deployed. When an intruder is detected by some sensors, several other sensors become awake to cover the trajectories of the intruder. The collected information about an intruder is reported to end users for analysis and processing.

- **Battlefield surveillance**: A wireless sensor network can be deployed in a battlefield for performing detection and tracking of target objects, such as tanks and vehicles, and sending real-time information about the enemy mobility to a central control unit. Precisely, a network should be able to detect and classify multiple targets, such as vehicles and troop movements, using sensors that are capable of sensing acoustic and magnetic signals generated by different target objects.

## 1.4 Motivations of This Book

There are several critical applications, such as intruder detection and tracking, where WSNs need to be deployed in a field in such a way that every point is sensed (or covered) by at least one sensor. In particular, it is sometimes desirable to deploy a dense wireless sensor network to achieve redundant coverage of a deployment field, where every point in the field is guaranteed to be covered by at least \( k \) sensors simultaneously and we say that the network is configured to provide \( k \)-coverage.

Our main interest in writing this book on \( k \)-covered WSNs is motivated by at least the following three applications, which require a degree of coverage that is at least equal to three, i.e., \( k \geq 3 \). First, to cope with the problem of sensor failures due to their fragility, the design of sensor networks for planet exploration [184] should be as reliable as possible since failed sensors in space cannot be easily diagnosed and replaced. Sun et al. [184] simulated a Confidence Weighted Voting technique on top of a \( k \)-cover deployment strategy. They showed that \( k \)-cover deployment with \( k \geq 3 \) is necessary to guarantee data redundancy, which improves data reliability and fault tolerance of sensing applications. Indeed, high coverage degree helps achieve higher sensing accuracy and stronger robustness against sensor failures. Second, multiple-sensor data fusion [121] was found to be useful for at least a three-sensor system, i.e., system whose degree of coverage is \( k \geq 3 \). Klein [121] discussed how this type of system helps detect, classify, and track the target objects. Since at least all the three sensors participate in the decision, it is unlikely that a false target would be detected as a true target. Third, the design of triangulation-based positioning systems [162] requires that each point in a target field be covered by at least three sensors. Nicules and Nath [162] showed that this type of positioning system helps increase the accuracy of the positions of the sensors.
The design of network configuration protocols for WSNs faces a challenging problem, namely energy conservation, due to the constrained battery power of the sensors. Several energy conservation protocols for WSNs networks have been proposed at the MAC and network layers, such as the ones suggested by Biswas and Morris [43], Casari et al. [56], and Zorzi and Rao [226, 227]. Moreover, a variety of energy-efficient coverage configuration schemes have been suggested, such as the ones proposed by Wang et al. [197], Xing et al. [205], and Zhang and Hou [218]. In general, the sensors are deployed with high density, and hence the design of network configuration protocols should benefit from this fact to provide k-coverage. It is well known that the best approach to save the energy of the sensors is duty-cycling so the sensors remain operational for as long as possible. Using a duty-cycling approach, the sensors can be turned on (i.e., active) or off (i.e., inactive) according to some sleep–wakeup scheduling protocol while guaranteeing k-coverage all the time. Achieving k-coverage becomes difficult especially in hostile environments, such as battlefields, where access to the sensors is not feasible or even impossible. This implies that the sensors cannot be always on but rather duty-cycled. Otherwise, they will deplete their energy and die quickly. Also, k-coverage of a field should use as minimum number of active sensors as possible to extend the network lifetime.

Before all, the main goal of sensor deployment is to monitor a field and report data to the sink for further analysis and processing. Hence, the sensors should also be able to forward data on behalf of each other. More importantly, the load of data forwarding should be evenly distributed amongst all the active sensors, which currently k-cover the field, so all the sensors have the same chance to relay data for others. This implies that the network of active sensors should be connected. Otherwise, the sensed data will not reach the sink. Indeed, network connectivity is required for data routing and information dissemination. Therefore, it is important that the network provide k-coverage while maintaining connectivity between all active sensors. In addition, it is well known that geographic forwarding is an energy-efficient and practical scheme for WSNs. Indeed, the sensors are not required to maintain global and detailed information on the topology of the entire network. The sensors need to only maintain local knowledge on their one-hop neighbours. Thus, for more effective sensor deployment, the load of k-coverage and data forwarding should be evenly distributed amongst all the sensors to maximize the network lifetime.

### 1.5 Design Requirements

In this section, we summarize the major requirements driving the design, analysis, and development of protocols for k-covered WSNs. Particularly, we identify those requirements that are necessary for building our unified framework, where coverage, duty-cycling, and geographic forwarding are jointly considered. These requirements are summarized as follows:

- **Energy Awareness:** The sensors have severe limitations in terms of storage, computational, communication, and sensing capabilities. In particular,
the sensors have scarce battery power (or energy). Thus, prolonging the network lifetime is the major challenge in the design and development of WSNs. With this in mind, it is essential that we design energy-aware protocols in all facets of the network operations, including sensor deployment, coverage and connectivity, scheduling, and data routing and dissemination.

- **On-Demand-Connected k-Coverage:** Several sensing applications prefer collecting redundant data to guarantee the most accurate decision-making process. Indeed, intruder detection and tracking applications may require more than one sensor to be active to collect information about the intruder (or malicious node) and track its motion accurately. Also, the sensors may die quickly because of their low energy, and thus, the network should be fault tolerant. Unlike most related work that focused on connected $k$-coverage with static sensors and fixed degree $k$ of coverage, where each point in a field is covered (or sensed) by at least $k$ sensors, our proposed framework supports mobile connected $k$-coverage, where a region of interest is $k$-covered using mobile sensors and $k$ may change over time. Also, the degree $k$ of coverage of a region of interest may not be the same for another region in the field. We call this on-demand connected $k$-coverage. Our framework adopts centralized and distributed strategies to ensure mobile connected $k$-coverage of a region of interest in a deployment field while maintaining network connectivity.

- **Autonomous and Purposeful Mobility:** In addition to their mobility, the sensors are autonomous, and thus are able to make their own decision based on the information they receive from the rest of the network. Particularly, these sensors should be able to move to designated locations in a region of interest whenever necessary to ensure its $k$-coverage and accomplish the target mission that has been determined by the sink. To account for mission-oriented WSNs, where the mobility of the sensors is controlled by the underlying mission, our framework enables purposeful mobility of the sensors and this mobility must be traded-off against the goals of the missions.

- **Situation Awareness and Intelligent Collaboration:** Situation awareness is an essential and critical foundation for successfully accomplishing all missions, and this requires intelligent collaboration between the sensors. Thus, all the sensors should be aware of any mission that has to be accomplished. This situation awareness assumes that there is a central entity, such as the sink, which decides the type of mission that has to be accomplished and in which region in the deployment field. This information should be propagated within the network while minimizing the total energy consumption needed to advertise this information about the mission.

- **Self-Organization:** The sensor mobility and scheduling may affect the topology of the network, which could possibly result in a connectivity-hole problem and/or a coverage-hole problem. One of the goals of our proposed framework is to make the sensors self-organizing and adaptive so they guarantee network connectivity, which is required for communication between the sensors, data forwarding from the sensors to the sink, and data
1.5 Design Requirements

dissemination from the sink to the sensors. Also, it enables the sensors to achieve any degree of coverage needed by an application for a mission.

- **Fault Tolerance:** In most sensing applications, the sensed data should be accurate to ensure better decision making by the sink. Also, data redundancy is desirable in that it increases data accuracy. For instance, in the intruder detection and tracking application, multiple sensors should be active to gather enough information about the intruder (or malicious node) and track its motion accurately. *Redundant coverage* (or *k*-coverage) ensures higher data redundancy and accuracy. Indeed, sensor nodes may deplete their energy and die. Hence, a network should tolerate the presence of faulty sensors and remains functional. Thus, *k*-coverage provides a high degree of fault tolerance of the network, where the value of *k* depends on the requirements of the application in terms of coverage.

- **Heterogeneity:** Unlike most related work that considered *k*-coverage with homogeneous sensors, our framework focuses on heterogeneous sensors, which do not necessarily have the same capabilities in terms of computation, storage, sensing and communication ranges, and initial energy. In real-world applications, WSNs are composed of heterogeneous sensors that have a potential to increase the network lifetime and reliability without causing significant increase in its cost. Indeed, as we mentioned earlier, the use of heterogeneous sensors helps reduce the probability of simultaneous failure of all the neighbours of a sensor [29].

- **Dimensionality:** In the literature, most of the works on WSNs dealt with two-dimensional settings, where sensors are deployed in a planar field. However, there exist several applications that cannot be effectively modeled in a two-dimensional space. For instance, sensors deployed on the trees of different heights in a forest, or in a building with multiple floors, or underwater applications [4, 5] require the design in a three-dimensional space. Moreover, oceanographic data collection, pollution monitoring, off-shore exploration, disaster prevention, and assisted navigation are typical applications of underwater sensor networks [5], which have to be designed using three-dimensional settings, which represent more accurately the network design for real-world applications.

- **Stochastic Features:** Although the majority of studies on wireless sensor networks considered the disk sensing model, where all sensor readings are assumed to be precise and have no uncertainty, the signal attenuation and the presence of noise associated with sensor readings require the use of a more realistic sensing model that reflects the real properties of the sensors. Precisely, the sensing capability of a sensor must be modelled as the probability of successful detection of an event, and hence should depend on the distance between it and the event as well as the type of propagation model being used (free-space vs. multi-path). Indeed, it has been shows that the probability that an event in a distributed detection application can be detected by an acoustic sensor depends on the distance between the event and the sensor [77]. Thus, the protocols designed for WSNs should account for the probabilistic nature of the sensor capabilities, and particularly, their sensing and communication ranges.
• **Data Delivery:** The main goal of the design of WSNs is to monitor a phenomenon in a field of interest and collect data related to that specific phenomenon. It is very important that the sensed data reach the sink for further processing. The accuracy of the decisions and actions taken by the sink depends on the availability of the data. Thus, the sensors should be able to use robust protocols that will enable them to deliver the data they have collected to the sink with high data delivery ratio. This issue depends on the data forwarding and dissemination capabilities of the sensors, which are in turn strongly dependent on the efficiency of the design of the corresponding routing protocols.

• **Delay:** For some time-critical sensing applications, such as forest fire detection and tracking, the sink should receive the sensed data collected by the sensors in a timely manner to avoid any undesirable consequence. It is necessary that the design of protocols for these types of sensing applications be conducted under the delay constraint so that the sensed data reach the sink within a certain time bound. In case the sensors are always on (or active), the data forwarding and dissemination protocol are responsible for meeting this delay constraint. However, when the sensors are duty-cycled, the duty-cycling protocols are also responsible to meet this delay bound.

### 1.6 Contributions of This Book

This book aims at investigating the following research problems, which are not totally disjoint. Each of these problems is introduced by a brief statement that is accompanied by a brief solution statement.

• **Almost Sure Connected Coverage:** What is the critical sensor spatial density above which a deployment field (respectively, network) is *almost surely* covered (respectively, connected)?

  We propose continuum percolation-based approaches to study phase transitions in coverage and connectivity in static WSNs in an integrated fashion. Precisely, we propose probabilistic approaches to compute the critical sensor spatial density above which a field is *almost surely* covered and the network is *almost surely* connected. Our proposed solutions consider both two-dimensional and three-dimensional deployment of the sensors. These solutions help the network designers achieve full coverage of a field with a minimum number of connected, active sensors, thus maximizing the network lifetime.

• **Connected k-Coverage:** What is a sufficient condition of the sensor spatial density for full k-coverage of a two-dimensional (respectively, three-dimensional) deployment field, where each point in the field is guaranteed to be covered by at least k sensors while maintaining network connectivity using static homogeneous sensors only under the assumption of a deterministic sensing model?
To solve this problem, thus supporting different applications and environments with diverse requirements in terms of coverage and connectivity using static sensors only, we extend our above analysis to $k$-coverage using a deterministic approach so the network self-configures to meet these requirements while considering a deterministic sensing model. To this end, we compute the active sensor spatial density that is necessary to achieve full $k$-coverage of a field while guaranteeing connectivity between all active sensors. Our analysis is based on Helly’s Theorem [44] and the geometric properties of the Reuleaux triangle (respectively, Reuleaux tetrahedron) in two-dimensional (respectively, three-dimensional) deployment fields. Using this analysis, we design randomized centralized protocols, pseudo-distributed protocols as well as fully-distributed protocols for connected $k$-coverage configurations in WSNs.

- **Heterogeneous Connected $k$-Coverage:** Given a field to be monitored, a positive integer $k \geq 3$, and a set $S$ of heterogeneous sensors, select a minimum subset of sensors $S' \subseteq S$ to stay on (or active) such that each point in the field is $k$-covered while the network induced by all the sensors in $S'$ is guaranteed to be connected.

We exploit the results obtained with the homogeneous model to solve the connected $k$-coverage problem for heterogeneous WSNs, where the sensors do not necessarily have the same sensing range, communication range, and initial energy. We show that while it is possible to design distributed protocols to guarantee connected $k$-coverage of a field using heterogeneous sensors while achieving good performance overall, it is impossible that a centralized protocol could be designed efficiently due to sensor deployment randomness and sensor heterogeneity. Thus, we propose a pseudo-random deployment approach, where the sensors are deployed in different layers in a circular deployment field with respect to the sink according to the strengths of their sensing and communication ranges as well as their initial energy. Based on this deployment strategy, we propose centralized and distributed protocols for generating energy-efficient connected $k$-coverage configurations using heterogeneous sensors.

- **Mobile Connected $k$-Coverage:** How to guarantee connected $k$-coverage in mission-oriented mobile WSNs under the following requirements? (i) **On-demand $k$-coverage:** A region of interest in a field should be $k$-covered whenever needed, where $k \geq 3$. Consequently, a region of interest to be $k$-covered does not have to be the same all the time and hence may change. (ii) **Network connectivity:** The sensors should be maintained connected for the correct network operation. (iii) **Sensor mobility:** The sensors should be able to move to designated locations in a region of interest to ensure its $k$-coverage whenever necessary.

We divide the problem of $k$-coverage in mission-oriented mobile WSNs into two sub-problems, namely sensor placement and sensor selection. The sensor placement problem is to compute the minimum number of sensors and their locations in a region of interest so that this region is $k$-covered. The sensor selection problem is to determine which sensors should move to the above-computed locations in the region while minimizing the total
energy consumption due to the mobility of the sensors and their communication. Specifically, we propose centralized and distributed approaches to solve the $k$-coverage problem in mission-oriented mobile WSNs. In the centralized approach, the sink designates a set of sensors to move towards specific locations in the region of interest to be $k$-covered. These locations are computed by the sink. In the distributed approach, the sensors compute the target locations, where the sensors should move to, and coordinate between themselves to $k$-cover a region of interest with *as small number of sensors as possible* (or simply *small number of sensors*). Our approach enables the sensors to move towards a region of interest and $k$-cover it while minimizing their mobility energy based on their closeness to the target locations in the region and the availability of other sensors.

- **Stochastic Connected $k$-Coverage**: Find a tight sufficient condition so that every point in a field is probabilistically covered by at least $k$ sensors with a probability no less than $p_{th}$, called *threshold probability*, under a stochastic sensing model and compute the required number of sensors. Then, select and schedule the sensors while providing stochastic $k$-coverage of a two-dimensional deployment field as well as connectivity between all the selected sensors.

  We adapt the results of the sensor scheduling problem for $k$-coverage of a two-dimensional deployment field under the deterministic sensing model, which is discussed earlier, to solve the sensor scheduling problem for stochastic $k$-coverage under *probabilistic* (or *stochastic*) sensing and communication models. It has been found that a stochastic sensing mode is more realistic than a deterministic (or binary) sensing model. Indeed, the former takes into account not only the distance between the sensors and the target locations but also the type of propagation model being used, i.e. free-space model or multi-path model. Under a stochastic sensing model, a point $p$ in a field is said to be *probabilistically $k$-covered* if the detection probability of an event occurring at $p$ by at least $k$ sensors is at least equal to some *threshold probability*, $0 < p_{th} < 1$. We propose a distributed stochastic $k$-coverage protocol, where each sensor runs a $k$-coverage candidacy algorithm to check whether it is eligible to turn itself *on* (or active). This helps us design a global framework for $k$-coverage in WSNs that considers both of the deterministic and stochastic sensing models.

- **Geographic Forwarding on Always-on Sensors**: How can data be forwarded in always-on WSNs while minimizing the total energy consumption of the sensors, thus maximizing the network lifetime?

  There is an ongoing debate on short-range versus long-range data forwarding in multi-hop wireless networks. This book supports the short-range data forwarding strategy for WSNs, where energy should be given the highest priority. More precisely, we propose an energy-efficient data forwarding protocol for WSNs so they remain operational as long as possible. Our protocol, called *Weighted Localized Delaunay Triangulation-based data forwarding* (WLDT), uses 1-lookahead scheme to guarantee data delivery to the sink. WLDT aims to minimize the average energy consumption of the sensors during data forwarding towards the sink. It ex-
exploits the geometric properties of the Delaunay triangulation [36] to build an energy-efficient path between a source and the sink as a sequence of sub-paths whose endpoints are called **checkpoints**. These checkpoints are selected based on their locations in the field and their remaining energy. A sub-path between a pair of checkpoints consists of a *series of forwarders*, which are the endpoints of short Delaunay edges and are selected based on their locations and remaining energy to forward the data between their corresponding checkpoints.

- **Energy-Delay Trade-off in Geographic Forwarding**: How to achieve minimum energy consumption of the sensors while ensuring uniform battery power (or energy) depletion of the sensors and meeting the required delay constraints in geographic forwarding in static WSNs?

  We propose a communication range slicing-based approach to trade-off between conflicting objectives of sensing applications, namely minimum energy consumption, minimum delay, and uniform energy depletion. Our approach aims to slice the communication range of the sensors into *concentric circular bands* and classify them with a goal to satisfy specific requirements of sensing applications in terms of energy consumption, delay, and energy depletion. First, we formulate the trade-off between these three conflicting goals as a multi-objective optimization problem which is solved using a *weighted scale-uniform-unit sum* approach. Then, we propose a data forwarding protocol for WSNs, which exploits our solution to the multi-objective optimization problem to find an optimum trade-off between three conflicting goals. For tractability, we consider a unit-disk communication model, where the communication ranges of the sensors are supposed to be circular and have the same radius. Then, we will discuss ways of relaxing these assumptions.

- **Energy Sink-Hole**: How and to what extent can a uniform energy depletion of all the sensors be guaranteed so as to avoid the energy sink-hole problem in always-on, static WSNs, where the sensors nearer the sink are heavily used in forwarding data to the sink on behalf of all other sensors, thus depleting their energy very quickly compared to all other sensors in the network? How can this problem be addressed in homogeneous, always-on WSNs?

  We show that static WSNs suffer from the energy sink-hole problem regardless of how efficient a geographic forwarding protocol is. We propose a solution to this problem by enabling sensors to adjust their transmission range when sending/forwarding sensed data to the sink. However, we prove that this solution imposes a severe restriction on the size of the deployment field. To alleviate this shortcoming, we propose another solution that suggests a sensor deployment strategy exploiting energy heterogeneity with a goal that the sensors in the network deplete their energy uniformly. When all the sensors have the same initial energy, we propose greedy, localized protocol, called energy aware Voronoi diagram-based data forwarding (EVEN), which exploits sink mobility and uses our proposed new concept of Voronoi diagram, called *energy aware Voronoi diagram*, where the locations of the sensors are time varying and are locally and virtually computed based on their remaining energy.
• **Geographic Forwarding on Duty-Cycled Sensors:** How to design energy-efficient geographic forwarding protocols with and without data aggregation in duty-cycled, $k$-covered WSNs in two-dimensional and three-dimensional deployment fields?

We design a unified framework for geographic forwarding on duty-cycled sensors. More specifically, we propose different approaches for both cases of two-dimensional and three-dimensional sensor deployment. In the former case, using a potential fields-based approach, we propose energy-efficient clustering-based geographic forwarding protocols for duty-cycled, $k$-covered WSNs with different levels of data aggregation. In the latter case, we focus on finding a trade-off between *uncertainty* due to duty-cycling with deterministic forwarding and *contention* due to opportunistic forwarding. Then, we propose a hybrid forwarding approach based on this trade-off. Indeed, in deterministic forwarding, a next best forwarder is determined *a priori.* Hence, duty-cycling introduces uncertainty at the sender side which is not totally certain that its selected next best forwarder would remain awake after data is being forwarded. In opportunistic forwarding, however, a next best forwarder is decided on-the-fly and after the data is transmitted. Thus, several active sensors may hear the transmitted data, thus creating high contention at the receiver side to select a next best forwarder.

• **Network Connectivity and Fault-Tolerance Measures:** What are the unconditional and conditional network connectivity and fault tolerance of $k$-covered WSNs that are deployed in two-dimensional and three-dimensional fields?

We benefit from our characterization of $k$-coverage in WSNs stated earlier and compute the traditional (or unconditional) connectivity of $k$-covered WSNs. Furthermore, we compute the conditional connectivity of $k$-covered WSNs based on the concept of *forbidden faulty set.* The latter shows that the classical connectivity used to capture network fault tolerance underestimates the resilience of large-scale networks, such as $k$-covered WSNs. Our measures consider both two-dimensional and three-dimensional deployment fields. We show that our measures of connectivity for the latter case are not a straightforward generalization of those for the former case.

### 1.7 Summary

In this chapter, we reviewed the main challenges in the design of WSNs as well as their potential applications. Then, we described the design metrics that drive the design process of these types of networks. Moreover, we presented the motivations behind writing this book. Furthermore, we gave an overview of the main contributions of this book by stating the research problems being investigated along with a brief description of our proposed solutions.