Chapter 2
Coverage, Connectivity, and Deployment in Wireless Sensor Networks

Yun Wang, Yanping Zhang, Jiangbo Liu and Rahul Bhandari

Abstract Recent years have witnessed successful real-world deployments of wireless sensor networks (WSNs) in a wide range of civil and military applications. Sensing coverage and network connectivity are two of the most fundamental issues to ensure effective environmental sensing and robust data communication in a WSN application. This chapter presents fundamental studies on the sensing coverage and the network connectivity from mathematical modeling, theoretical analysis, and performance evaluation perspectives. Both lattice WSNs that follow a pattern-based deployment strategy and random WSNs that follow a random deployment strategy are considered. The aim of this chapter is to deliver a systematic study on the fundamental problems in WSNs and provide guidelines in selecting critical network parameters for WSN design and implementation in practice.

Keywords Coverage · Connectivity · Deployment · Wireless sensor networks

2.1 Introduction to Wireless Sensor Network

A wireless sensor network (WSN) is made up of tens to thousands of interconnected sensors that are randomly or deterministically deployed in a field of interest to monitor various environmental changes such as light, temperature, air pressure,

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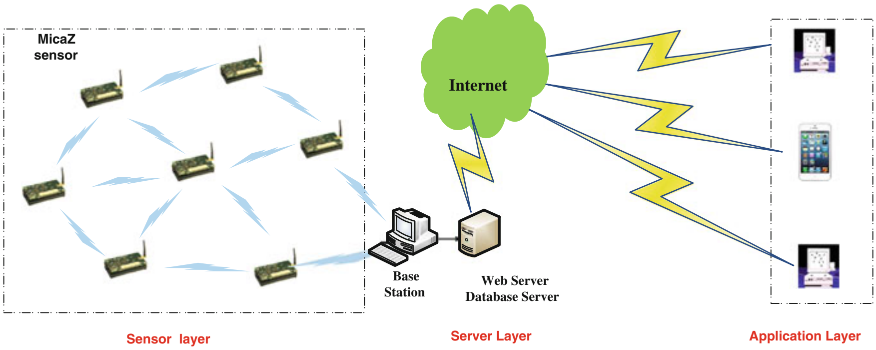


Fig. 2.1 Illustration of a wireless sensor network where sensors periodically sense and detect application-specific events and report the sensing data to a BS for data aggregation, analysis, and visualization

humidity, pollution, etc. Figure 2.1 illustrates a typical WSN where a number of MicaZ[1] sensors are deployed in a square field of interest to monitor several application-specific environmental events. All sensors are connected to a base station (BS) via wireless communication links, and the sensing data are periodically collected and aggregated at the BS. The BS can be connected to a designated Web server that makes it possible for authorized users to remotely access and configure the WSN anytime, anywhere via traditional computers and mobile devices such as iPhone, iPod, iPad, smart phones, etc. MoteLab, for example, is a Web-based sensor network test bed at Harvard University where a set of permanently deployed sensors is connected to a central Web server which provides a Web interface for data accessing and logging, sensor reprogramming, task creating, and scheduling on the test bed [1].

The unit of a WSN is sensor node. Each sensor node has four major components: (1) sensing transducer, (2) data processor, (3) radio transceiver, and (4) embedded batteries [2]. Figure 2.2 illustrates the main components of a MicaZ sensor. The sensing transducer first measures the environmental conditions in its surrounding within certain sensing range and then the data processor transforms the sensed data into an electric signal. After that, the radio transceiver transmits the processed signal to a BS through a direct communication path or a multi-hop communication path for data fusion. All the operations including sensing, computation, and communications are powered by the embedded batteries that are usually non-rechargeable.

[1] Source for MicaZ sensors is available at http://www.openautomation.net/uploadsproductos/micaz_datasheet.pdf.

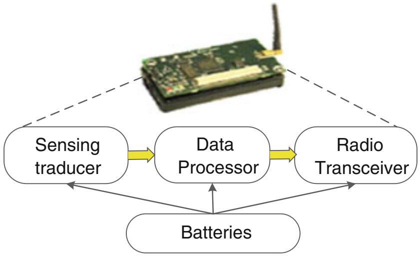


Fig. 2.2 Four major components in a sensor node

2.2 Applications of Wireless Sensor Networks

WSNs are emerging as a new computing platform and networking structure to couple the physical world around us with digital world [3]. It enables novel applications in a wide range of disciplines [4] such as environmental monitoring, habitat monitoring, industrial and manufacturing automation, health care [5], and intrusion detection and tracking. This is due to the fact that consistent sensing data collected by a WSN makes it possible for engineering scientists and engineers to derive quantitative measurements of the dynamics of environmental conditions to either have a better understanding of the monitored field or to capture the occurrence of a set of application-desired events, so as to take appropriate actions whenever needed. Typical applications of WSNs include, but not limited to:

- *Environmental Observation and Forecasting Systems* (EOFS): EOFS is a distributed WSN system designed to monitor, model, and forecast wide-area physical systems such as river systems, transportation, and agriculture for natural resource planning and disaster response [6].
- *Endangered Species Recovery*: To assist the recovery of rare and endangered species of plants, a set of sensors are used to monitor various ecological conditions such as temperature, humidity, rainfall, wind, and solar radiation near endangered plants. Collected data can be used to investigate why a species is rare and to evaluate possible remedial actions [7].
- *Habitat Monitoring* [8, 9]: An application of WSN to monitor the habitat of sensible wildlife through sampling the environmental changes in terms of temperature, humidity, barometric pressures, and midrange. As an example, in 2002, about three dozen UC Berkeley Motes were deployed on Great Duck Island, Maine, to monitor the microclimates in nesting burrows used by the Leach's storm petrel and study the habitat of storm petrel [10].
- *Intrusion Detection and Tracking*: Detection, classification, and tracking of intruders/targets/objects are a basic surveillance or military application of WSN [11] and have been studied in the literature from many aspects [11–18]. Such applications concern how fast the WSN can detect certain intruders/targets/objects and how reliably the sensing and detection data can be reported to the BS.
- *Structural and Seismic Monitoring* [19–21]: An application of WSN in the field of civil engineering to monitor the condition of civil structures such as

buildings, bridges, roads, and aircrafts for instrumentation. It is considered as substitutes for traditional tethered monitoring systems due to its low cost, ease of deployment, and lack of wiring.

2.3 Preliminaries

In a WSN, every sensor has a limited sensing range, denoted as $r_{s,}$ and a limited communication range, denoted as r_c. The union of the sensing ranges of all sensors is defined as the network *sensing coverage* [22], which reflects how well the area of sensor field is monitored. In addition, to communicate successfully, a WSN must provide satisfactory *network connectivity*, so as to eliminate the isolation of sensors and enable each sensor to report its sensing data to its fusion center [23]. In order to understand the sensing coverage and network connectivity in a WSN, several fundamental models including network deployment model, sensing model, and communication model must be introduced.

2.3.1 Network Deployment Model

According to the accessibility of the monitored area, there are two primary sensor deployment strategies: (1) *deterministic sensor deployment* in a controlled and human-friendly environment [24] and (2) *random sensor deployment* in a dangerous and inaccessible region [25]. Generally speaking, the pattern-based lattice WSNs resulting from deterministic sensor deployment provide better sensing coverage and higher degree of connectivity [26], comparing to the random counterparts. On the other hand, it was found in [27, 28] that deterministic sensor deployment does not always outperform the random sensor deployment for applications that do not require full coverage such as intrusion detection.

Assume that the field of interest is a two-dimensional square region with area $A = L \times L$. A number of N sensors are deployed in the target region A, and the location of sensor i is represented by (x_i, y_i), for $i = 1,\ldots, N$, over the two-dimensional region. In a lattice WSN, the sensors' locations conform to the geographical pattern shapes. On the other hand, in a WSN following a random and uniform sensor deployment, the probability density function (PDF) for a sensor at location (x_i, y_i) is given by $f(x_i, y_i) = \frac{1}{A}$.

Figures 2.3 and 2.4 illustrate a square pattern-based lattice WSN and a randomly and uniformly distributed WSN, respectively, where 100 sensors are deployed in a square region of interest with area $A = 100 \times 100$. In addition, the Voronoi diagrams of both WSNs are depicted [29].

Voronoi diagram of a WSN presents the proximity information about the deployment sensors in the field of interest [30]. To be specific, the Voronoi diagram

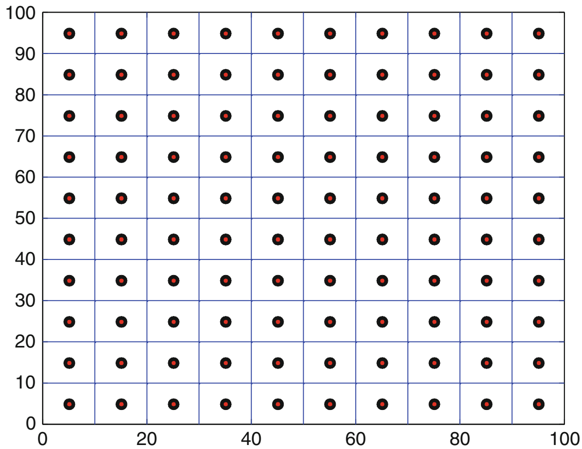


Fig. 2.3 Voronoi diagram of a square pattern-based lattice WSN

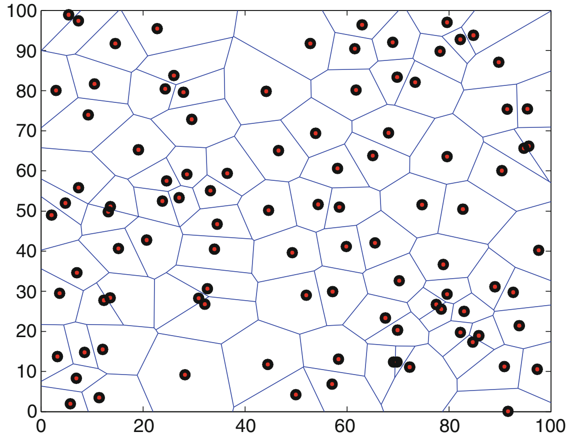


Fig. 2.4 Voronoi diagram of a random WSN

of the N sensors partitions the field of interest into N Voronoi polygons. Each sensors has a Voronoi polygon, where all the inside points are closer to it than to any other sensors [31, 32]. It is clear that the Voronoi polygon for each sensor is the same for all sensors in a lattice WSN. This property can be exploited to analyze the deployment efficiency of lattice WSNs [29, 30, 33], to be discussed in Sect. 2.4.

2.3.2 Network Connectivity

The communication typology of a WSN can be modeled as a graph, denoted by $G = (V, E)$, where V is the set of sensor vertices and E is the set of wireless communication links, i.e., the line segments connecting neighboring sensors. A pair of sensors is said to be *neighbors* of each other if their Euclidean distance is at most the communication range r_c, according to the *disk communication model*. As illustrated

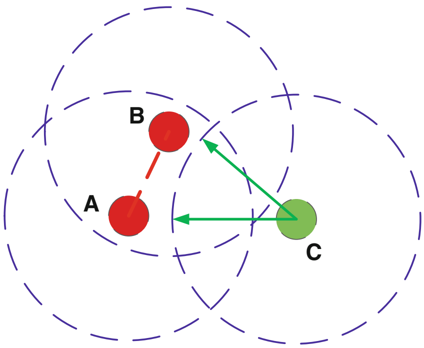


Fig. 2.5 Communication links in a WSN graph

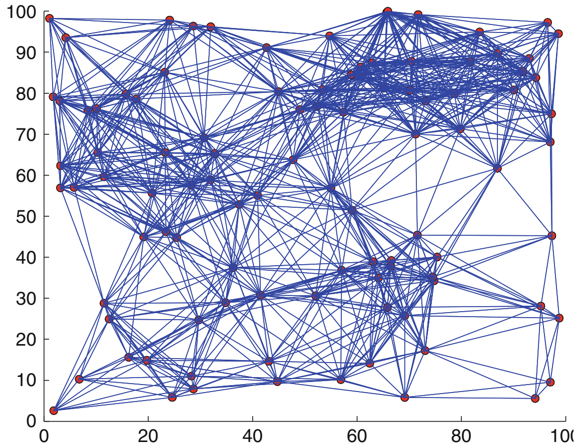


Fig. 2.6 Illustration of a connected WSN graph where 100 sensors are randomly and uniformly deployed in a square region with area 100 × 100 m^2, the communication range is set as 30 m

in Fig. 2.5, sensors A and B are neighbors and there is a bi-directional link between them as they are within each other's communication range while sensor C is isolated.

A WSN is defined as *connected* if, for any two sensors, there is a single-hop or multi-hop communication path between them consisting of consecutive wireless communication links. The WSN connectivity is primarily determined by the sensors' deployment locations and the communication ranges. Figure 2.6, for example, illustrates a *connected* graph of a WSN, where 100 sensors are randomly deployed at a square region with area 100 × 100 m^2 and the communication range of each sensor is set at 30 m. As a contrast, Fig. 2.7 depicts an *un-connected* graph for the WSN when the sensor's communication is reduced to 15 m.

Note that the disk communication model is widely adopted in the state-of-the-art study on the network connectivity of a WSN; however, it is challenged by empirical measurements where the wireless links are found to be highly irregular and far from being isotropic due to multi-path and shadowing effect as well as the environmental noises and interferences [34]. The ``signal-to-interference-plus-noise'' ratio (SINR) model and the log-normal shadowing model can be adopted to capture these effects as described in [35].

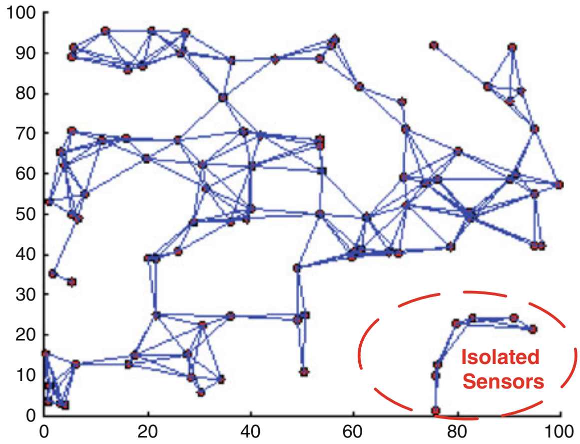


Fig. 2.7 Illustration of an *unconnected* WSN graph where 100 sensors are randomly and uniformly deployed in a square field of 100 × 100 m^2, the communication range is set as 15 meters

2.3.3 Network Coverage

A WSN is deployed in a region of interest to monitor certain environmental conditions or changes in an application. A point is covered by a sensor if the Euclidean distance between the point and the sensor is no more than the sensing range r_s according to the *disk/Boolean sensing model* [36, 37]. Disk sensing model is widely used due to its simplicity and the fact that it enables theoretical abstraction and analysis. Mathematically speaking, a point p is covered by a sensor s_i, if and only if,

$$d(s_i, p) \leq r_c, \tag{2.1}$$

where $d(s_i, p)$ is the Euclidean distance between point p and the sensor s_i.

For *full sensing coverage*, the entire region of application field is covered by at least one sensor and there is no sensing coverage hole in the network. Figures 2.8

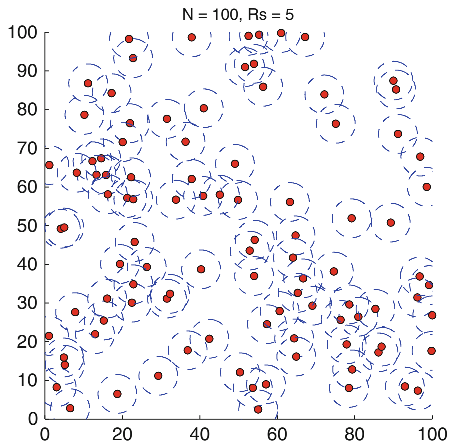


Fig. 2.8 Sensing coverage of a random WSN with 100 sensors and sensing range *R5* = 5 m. The field of interest is *not fully* covered

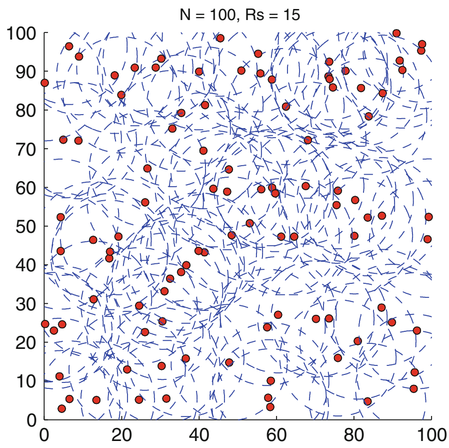


Fig. 2.9 Sensing coverage of a random WSN with 100 sensors and sensing range *R*5 = 15 m. The field of interest is nearly fully covered

and 2.9 represent the sensing coverage of a random WSN with 100 sensors for sensing range $r_s = 5$ and $r_s = 15\,\text{m}$, respectively.

The disk sensing model may not be able to simulate the sensing capability of a real-life sensor accurately, because realistic sensors are designed to be small and cheap that they are unlikely to be sophisticated enough to provide exactly the same detection capability in every direction. A probabilistic model, *Elfes sensing model* [38, 39], is therefore used in the literature to better model the realistic sensing capability of a real-life sensor.

Following the Elfes sensing model, the probability that a sensor detects an event to a distance *d* is [38, 39]:

$$P(d) = \begin{cases} 1, & d < (r_s - e); \\ e^{-a(r-r_s)^{\gamma}}, & (r_s - e) \le d \le (r_s + e); \\ 0 & d > (r_s + e); \end{cases} \tag{2.2}$$

where r_s is the average sensing range, *e* is a measure of the sensing uncertainty in sensor's detection capability, and α and γ are device-oriented parameters. To be specific, a sensor can detect an event at a distance less than r_s - *e* with probability 1, at a distance greater than r_s + *e* with probability 0, and in the distance interval $(r_s - e, r_s + e)$ with probability $e^{-a(r-r_s)^{\gamma}}$ [35, 40]. Figure 2.10 depicts the sensing and detection probability of a sensor under the Elfes sensing model and the Boolean sensing model when $r_s = 5$ and *e* = 3.

Note that Boolean sensing model can be regarded as a special case of Elfes sensing model by setting *e* = 0. A study on the impacts of sensing models on the sensing coverage of a WSN is presented in [39].

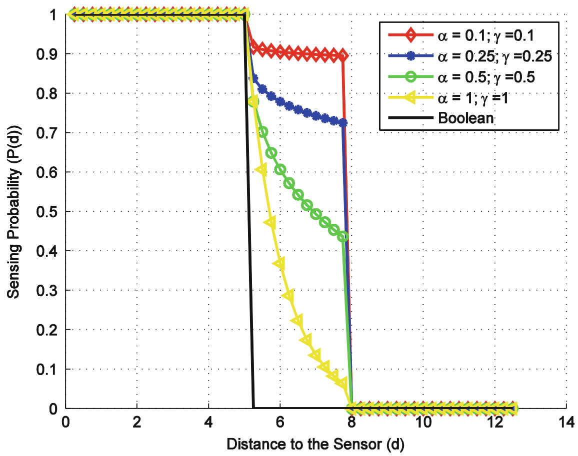


Fig. 2.10 Elfes sensing model

2.4 Coverage and Connectivity in Lattice WSNs

In lattice WSNs, sensors are deliberately and precisely placed at desirable locations in a controlled fashion following regular patterns. Popular patterns including *square, triangle, and hexagon* that can be repeated to cover a continuous region without having any overlapping areas are widely adopted in practice due to the simplicity and the convenience of deployment. Other patterns such as rhombus and mutated patterns [30, 41, 42, 43, 44] are also investigated in the literature in terms of minimizing the required number of sensors while providing desirable quality of service (QoS) for various application contexts. Here, we focus on the three popular patterns and compare their efficiency in providing *full sensing coverage*, *full network connectivity*, and *full sensing coverage with connectivity* under the same application context.

Figure 2.11 illustrates the Voronoi polygon area for a sensor in a lattice WSN following a square, a triangular, and a hexagonal pattern, respectively. It was pointed out in [32] that the area of the Voronoi polygon for a sensor represents the average contribution to the network QoS such as sensing coverage and communication

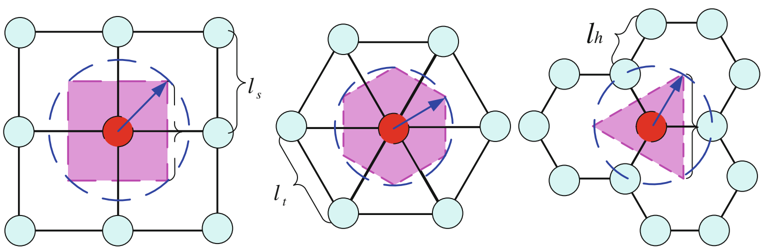


Fig. 2.11 Voronoi polygon for a sensor in a lattice WSN following a *square*, a *triangular*, and a *hexagonal* pattern, respectively [29]

connectivity. It also determines the required number of sensors. To be specific, given an application field with area A and assuming A_s is the area of the Voronoi polygon for a sensor in a lattice WSN, the number of deployed sensors can be estimated as:

$$N = \frac{A}{A_s}. \tag{2.3}$$

The area of the Voronoi polygon for a sensor is determined by the side length of the deployment pattern, i.e., the deployment distance l_x. The deployment distance is determined by the sensor's capability of sensing range r_s, communication range r_c, and the application requirements on sensing coverage and connectivity.

2.4.1 Full Connectivity in Lattice WSNs

For *full connectivity*, the side length of the deployment pattern should be no more than the communication range, i.e., $l_x \leq r_c$. Optimally, the side length of the deployment pattern is set as the communication range r_c for maximum deployment efficiency in that minimum sensors are needed. Specifically, to provide full connectivity, the maximum area of the Voronoi polygon for each sensor is given as [29]:

$$A_s(\text{Con}) = \begin{cases} l_s^2 = r_c^2, & \text{square} \\ \frac{\sqrt{3}}{2} l_t^2 = \frac{\sqrt{3}}{2} r_c^2, & \text{triangular} \\ \frac{3\sqrt{3}}{4} l_h^2 = \frac{3\sqrt{3}}{4} r_c^2, & \text{hexagonal} \end{cases} \tag{2.4}$$

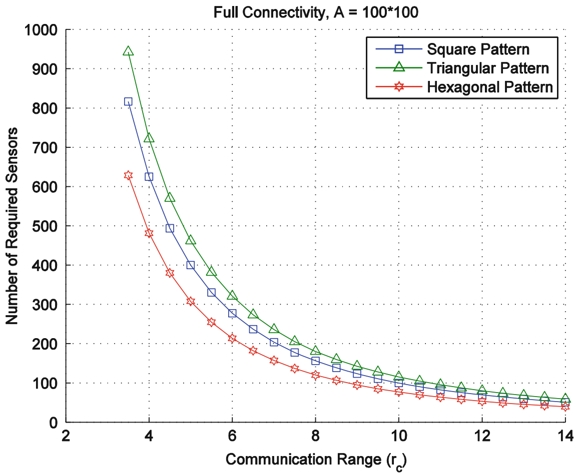
for a square, a triangular, and a hexagonal pattern-based WSN, respectively.

Combining Eqs. (2.3) and (2.4), the required number of sensors to achieve full connectivity in a square field of interest with area A = 100 × 100 m^2 is plotted in Fig. 2.12 for the three considered patterns. The communication range is varied from 3.25 to 14 m, and the required number of sensors changes from about 900–100 in the studied cases. It can be observed that *hexagonal* pattern is the optimal deployment pattern in terms of needing the minimum number of sensors as compared to the square and triangular patterns for full connectivity. Note that 4-connectivity, 6-connectivity, and 3-connectivity are automatically provided in fully connected lattice WSN following a square, a triangular, and a hexagonal pattern, respectively.

2.4.2 Full Coverage in Lattice WSNs

On the other hand, for full sensing coverage, the maximum side length of the Voronoi polygon for a sensor should be $\sqrt{2}r_s$, r_s, and $\sqrt{3}r_s$ for a square, a triangular,

Fig. 2.12 Number of required sensors for full connectivity in a lattice WSN following a *square*, a *triangular*, and a *hexagonal* pattern, respectively



and a hexagonal pattern-based lattice WSN, respectively, based on the geometry illustrated in Fig. 2.11. The maximum area of the Voronoi polygon is thus computed as [29]:

$$A_5(\mathrm{Cov}) = \begin{cases} 2r_s^2, & \text{square} \\ \frac{3\sqrt{3}}{2}r_s^2, & \text{triangular} \\ \frac{3\sqrt{3}}{4}r_s^2, & \text{hexagonal} \end{cases} \tag{2.5}$$

for a square, a triangular, and a hexagonal pattern-based WSN, respectively.

Similarily, combining Eqs. (2.3) and (2.5), we have the required number of sensors to achieve full sensing coverage in a square field of interest with area $A = 100 \times 100$ m^2 for the three considered patterns as illustrated in Fig. 2.13. In this figure, the sensing range is varied from 2 to 10 m. It can be observed that *triangular* pattern is the optimal deployment pattern in terms of needing the minimum number of sensors as compared to square and hexagonal patterns for full sensing coverage.

2.4.3 Full Coverage and Connectivity in Lattice WSNs

To achieve both full sensing coverage and full connectivity in a WSN where each point in the field of interest should be covered and all sensors in the network is connected; the above analysis on the sensing coverage and the network connectivity should be combined. To be specific, Eqs. (2.4) and (2.5) give the maximal area of the Voronoi polygon $A_5(\mathrm{Con})$ and $A_5(\mathrm{Cov})$ for a given sensor in the three considered lattice WSNs for full connectivity and full sensing coverage, respectively. The smaller one, i.e., $\min(A_5(\mathrm{Con}), A_5(\mathrm{Cov}))$, is the design bottleneck and

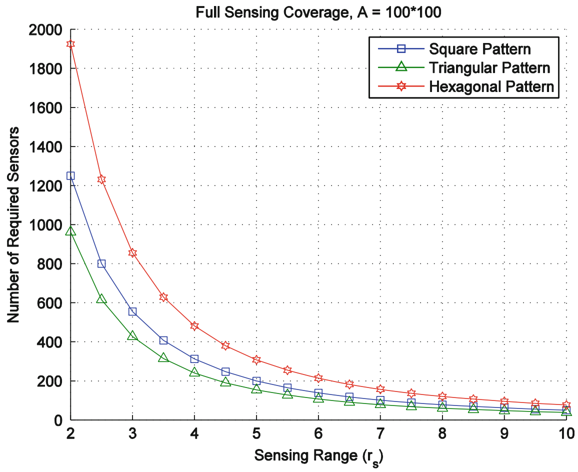


Fig. 2.13 Required number of sensors for full sensing coverage in a lattice WSN following *square*, *triangular*, and *hexagonal* patterns

determines the maximal area of the Voronoi polygon of a sensor for both full sensing coverage and full connectivity and is given by [30]:

$$A_s(\mathrm{Cov},\mathrm{Con}) = \begin{cases} \min(2r_s^2, r_c^2), & \text{square} \\ \min\left(\frac{3\sqrt{3}}{2}r_s^2, \frac{\sqrt{3}}{2}r_c^2\right), & \text{triangular} \\ \min\left(\frac{3\sqrt{3}}{4}r_s^2, \frac{3\sqrt{3}}{4}r_c^2\right), & \text{hexagonal} \end{cases} \tag{2.6}$$

for a square, a triangular, and a hexagonal pattern-based WSN, respectively.

Clearly, the ratio of the sensing range to the communication range plays an important impact on the area of the unit Voronoi polygon for each sensor and the deployment efficiency. Combining Eqs. (2.3) and (2.6), we have the required number of sensors to achieve both full sensing coverage and full connectivity in a region of interest with area $A = 100 \times 100\ \mathrm{m}^2$ for the three considered patterns as illustrated in Fig. 2.14. In this analysis, the communication range is fixed at 5 and the sensing range is varied from 2.25 to 7.25 to generate different ratios of sensing range to communication ranges (varies from 0.45 to 1.45). It can be observed in the figure that the ratio of sensing range to communication range determines the optimal deployment pattern for the minimum required number of sensors and no pattern is always the best for all the cases.

Specifically, triangular pattern is the optimal one when $r = \frac{r_s}{r_c} \le 0.6580$, square pattern outperforms the other two patterns when $0.6580 < r = \frac{r_s}{r_c} < 0.8772$, and hexagonal pattern is the best pattern when $r = \frac{r_s}{r_c} \ge 0.87725$. Bai et al. discussed more patterns and their efficiencies in [30, 41, 42, 43, 44].

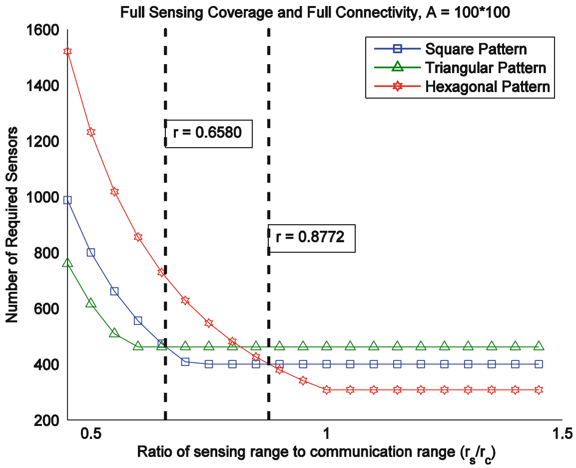


Fig. 2.14 Required number of sensors for both full sensing coverage and full connectivity in a lattice WSN following a *square*, a *triangular*, and a *hexagonal* pattern

2.5 Coverage and Connectivity in Random WSNs

Random deployment is appealing for large-scale WSN applications, where sensors can be dropped from a low-flying airplane or an unmanned aerial vehicle (UAV). This deployment strategy is easily scalable and is appropriate for a hostile environment in many civil and military applications such as contaminant transport monitoring and intrusion detection [45]. The sensing coverage and network connectivity based on a random WSN model have been extensively investigated in the literature [46–57].

2.5.1 Coverage of Random WSNs

In a random WSN where a number of N sensors are deployed independently and uniformly in a bounded field of interest A as illustrated in Fig. 2.15, the node density is $p = N/A$. Assuming the disk sensing model where each sensor can monitor any point whose distance to the sensor is no more than the sensing range r_s, the network sensing coverage is derived as [37, 53, 58]:

$$P\mathrm{cov} = 1 - e^{-p\pi r_s^2} \tag{2.7}$$

Consider an arbitrary point T, the probability that there exist n sensors in the circular area S_T centered at T with radius r_s is Poisson distributed and can be derived as:

$$P(n, T) = \frac{(pS_T)^n}{n!} e^{-pS_T}, \tag{2.8}$$

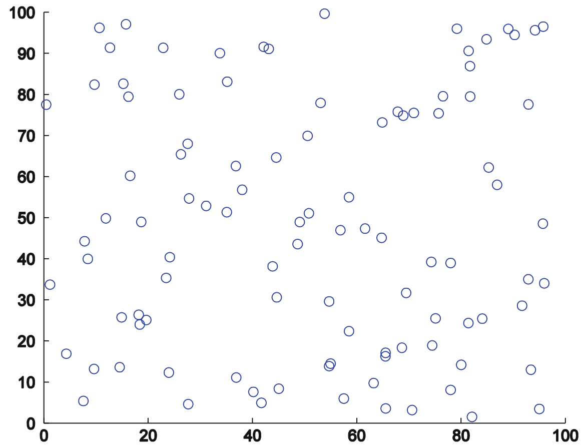


Fig. 2.15 An example random WSN with 100 independently and uniformly deployed sensors

where $S_T = \pi r_s^2$. The probability that there is no sensor (i.e., $n = 0$) deployed in S_T is derived as:

$$P(0, T) = e^{-p\pi r_s^2}. \tag{2.9}$$

Hence, the probability that there is at least one sensor deployed in the S_T (the point T is covered by at least one nearby sensors) can be computed as:

$$P\text{cov}(T) = 1 - e^{-p\pi r_s^2}. \tag{2.10}$$

As the N sensors are independently and uniformly distributed over the entire field of interest, all points in the field of interest have identical probability of being covered. Thus, the network sensing coverage is:

$$P\text{cov} = Pcv(T) = 1 - e^{-p\pi r_s^2}. \tag{2.11}$$

Figure 2.16 illustrates the numerical results of the network sensing coverage versus the sensing range for different numbers of deployed sensors, i.e., $N = 100$, 200, 300, 400, and 500, respectively. It is clear that the network sensing coverage is jointly determined by the network node density ($p = N/A$) and the sensors' sensing range r_s. Increasing sensors' sensing range and/or increasing the node density can be used to increase the network sensing coverage. On the other hand, given an application-specific sensing coverage requirement Pcov and sensors' sensing range r_s, the required number of sensors can be determined according to Eq. (2.11). A recent survey on the Coverage Problems in Sensor Networks is provided in [59].

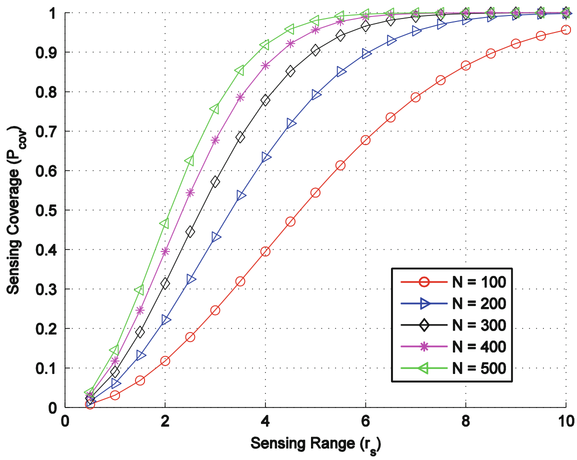


Fig. 2.16 Probability that any point in the WSN field of interest is covered by at least one nearby sensor(s), i.e., the sensing 1-coverage of a random WSN with respect to the sensing range

2.5.2 Connectivity of Random WSNs

Network connectivity is another fundamental problem in WSNs to ensure the data communication among sensors and the BS. A sensor is said to be connected if and only if it has a direct or multi-hop communication path to the BS. A WSN is said to be connected if all sensors are connected. Figures 2.6 and 2.7 illustrate a connected WSN and un-connected WSN, respectively. It is clear that in a connected WSN, there is no isolated sensor(s) in the network. A sensor is said to be isolated if its node degree is zero. The node degree of a sensor is the number of neighbors within its communication range r_c. As illustrated in Fig. 2.5, node *C* is an isolated sensor and has no neighbor within its communication range.

Consider an arbitrary sensor s_i in the network, the probability that it is isolated is equivalent to the probability that there exists no neighboring sensor within its communication range and follows:

$$P_{iso}(s_i) = e^{-p\pi r_c^2}. \tag{2.12}$$

The probability that sensor s_i is *not* isolated is:

$$P_{\text{non-iso}}(s_i) = 1 - e^{-p\pi r_c^2}. \tag{2.13}$$

As all *N* sensors are independently and uniformly deployed in the field of interest, they have the same probability of being non-isolated. Thus, the probability that there is no isolated sensor in the WSN is given as:

$$P_{\text{non-iso}} = \prod_{i=1}^{N} P_{\text{non-iso}}(s_i) = \left(1 - e^{-p\pi r_c^2}\right)^N. \tag{2.14}$$

The event that there is no isolated sensor in the WSN is a necessary (but not sufficient) condition for a WSN to be connected. It gives the *upper bound* of the network connectivity. Further, it is found in [50–52] that a geometric random graph resulting from a random WSN that attains the property that all sensors have at least K neighbors is asymptotically equal to the property that the WSN has K-connectivity [19]. In other words, a WSN in which all sensors have at least one neighbor (i.e., there is no isolated sensor) implies that the WSN is connected with a high probability, i.e.,

$$P_{\text{con}} = P_{\text{non-iso}} = \left(1 - e^{-p\pi r_c^2}\right)^N, \tag{2.15}$$

for $P_{\text{non-iso}}$ is almost one [51].

Figure 2.17 shows the probability that the WSN is connected with respect to the communication range (r_c) for different numbers of deployed sensors in the square field of interest with area A = 100 × 100 m^2. It can be observed that there exists a critical communication range above which there is a high probability that the WSN is connected. The critical communication range is jointly determined by the sensor distribution and the communication range.

Note that for a WSN to function well, both sensing coverage and connectivity should be ensured. One of the fundamental results on integrated sensing coverage and connectivity is stated as: *If the communication radius of sensors is at least twice the sensing range, i.e., $r_c = 2\ r_s$, then the sensing 1-coverage of a bounded field of interest is sufficiently to guarantee 1-connectivity of the WSN* [35, 48, 49].

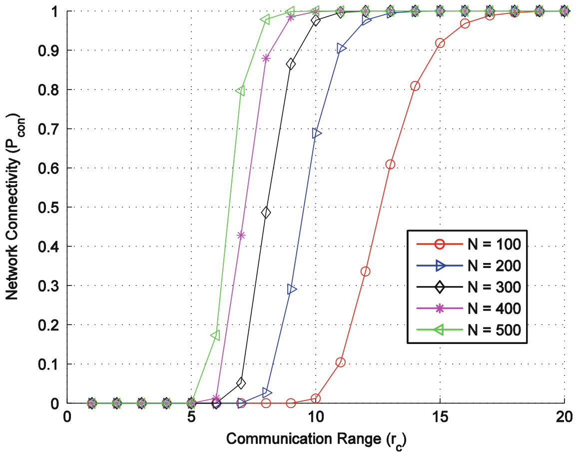


Fig. 2.17 Probability that a random WSN is connected with respect to the communication range for different numbers of deployed sensors in square field of interest with area A = 100 × 100 m^2

2.6 Summary

In this chapter, we have introduced three fundamental problems: sensing coverage, network connectivity, and sensor placement/deployment in a WSN. Sensing coverage reflecting how well the WSN field of interest is covered and communication connectivity describing how reliable the sensing information can be gathered at the BS are the two of the most basic QoS requirements in a WSN. We have presented the analysis on sensing coverage, connectivity, and connected coverage for lattice WSNs following pattern-based deployment strategy and random WSNs following a random deployment strategy, respectively. In literature, the open problems in this direction include sensing coverage and connectivity analysis in three-dimensional WSNs, non-uniformly distributed WSNs, and mobile WSNs.

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