COVERAGE AND COVERAGE CONTROL

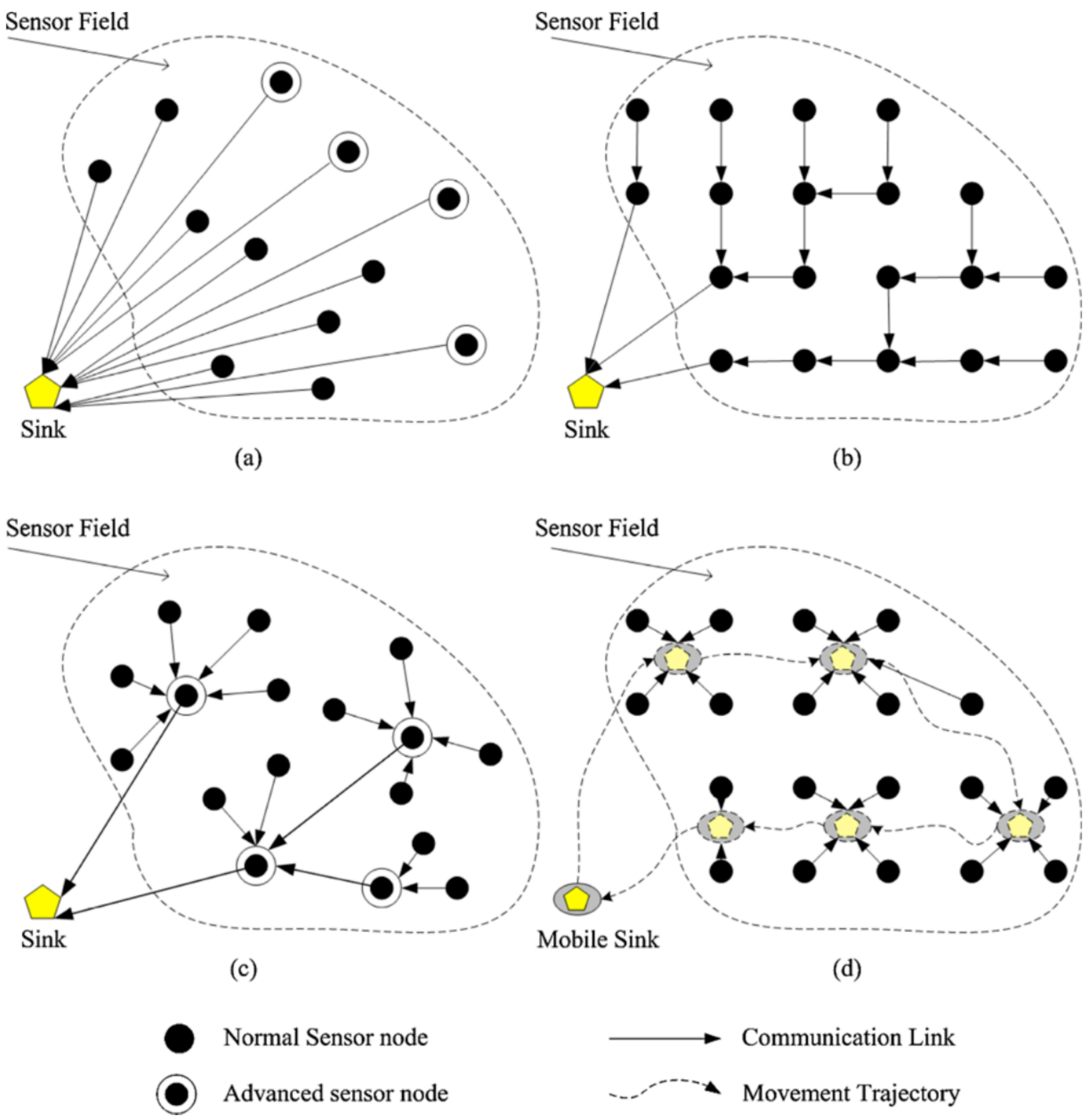
THE COVERAGE PROBLEM

The coverage problem is a fundamental problem in WSNs as it has a direct impact on the sensors energy consumption and the network lifetime.

The coverage problem can generally refer to how to effectively and efficiently monitor the network field effectively.

Coverage problems can be classified: according to the frequency of network field monitor, into either continuous coverage problems or sweep coverage problems.

Continuous coverage problems can be further classified, according to the region of interest for monitoring, into three types: area coverage, point coverage, and barrier coverage.



THE COVERAGE PROBLEM

Furthermore, coverage problems can be classified, according to the required coverage degree, into either 1−coverage problems or K−coverage problems.

On the other hand, coverage protocols can be classified based on the connectivity requirement, to either connectivity aware coverage protocols or non−connectivity aware coverage protocols.

Furthermore, coverage protocols can be classified, according to the adopted algorithm characteristics, into either distributed protocols or centralized protocols.

Centralized coverage protocols can be further classified into either evolutionary algorithm (EA) based protocols or non−EA based protocols. Moreover, coverage protocols can be classified according to the system model of the network.

COVERAGE AND SYSTEMS MODEL

There are four features under the system model:

- ✓ Sensor location awareness (aware or unaware),
- ✓ Sensor mobility models (static, mobile or hybrid of both),
- ✓ Sensor deployment models (deterministic or random), and
- ✓ Sensor sensing model.

Sensing models are broadly classified, based on the sensing ability, into two types:

- ✓ Deterministic sensing models and
- ✓ probabilistic sensing models.

Sensing models can also be classified, based on the direction of the sensing range, into either

- ✓ Directional sensing models or
- ✓ Omnidirectional sensing models.

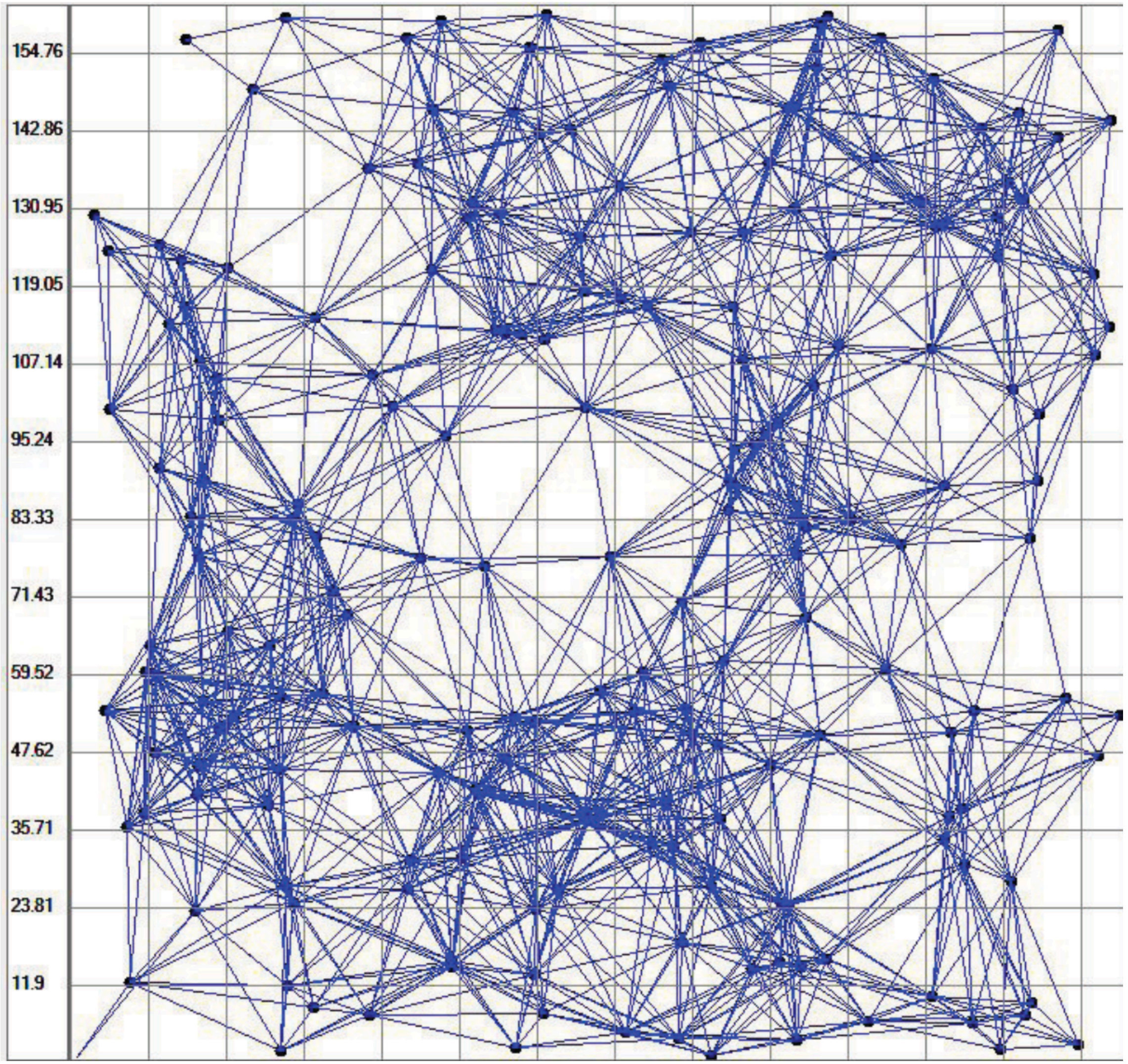
Coverage protocols can also be classified based on when the coverage optimization happens, i.e. into either

- ✓ Coverage–aware deployment protocols, when coverage optimization happens before the deployment stage, or
- ✓ sleep scheduling protocols, when coverage optimization happens after the deployment stage.

Sleep scheduling protocols can be further classified, based on the network topology, into either cluster-based sleep scheduling protocols or sleep scheduling protocols for flat networks.

SENSOR COVERAGE ISSUES

- Sensor Coverage Model
- Network Coverage Control
- Node Placement Optimization
- Coverage Lifetime Maximization
- Area Coverage Problems
- Critical Sensor Density
- Sensor Activity Scheduling
- Node Movement Strategy
- Barrier Coverage Problems
- Build Intrusion Barriers
- Find Penetration Paths
- A Voronoic Diagram and Delaunay Triangulation.



SENSOR COVERAGE MODEL

Sensor coverage models are used to reflect a sensors' sensing capability and quality.

They are abstraction models to quantify how well sensors can sense physical phenomena at some locations, or in other words, how well sensors can cover such locations.

In almost all cases, sensor coverage models can be mathematically formulated as a coverage function of distances and angles.

The inputs of such a coverage function are the distances between a particular space point and sensors' locations, and the output is a nonnegative real–valued number and is called *coverage measure* of this space point.

In some cases, a space point is said to be covered if its coverage measure satisfies some predefined threshold.

On the other hand, sensor types are diverse, and each sensor type has its own manner of sensing physical stimuli.

Also application scenarios are various, and each application scenario has its own way of interpreting sensory data. As such, sensor coverage functions can be defined in different forms and are subject to different interpretations, depending on sensor types and application scenarios.

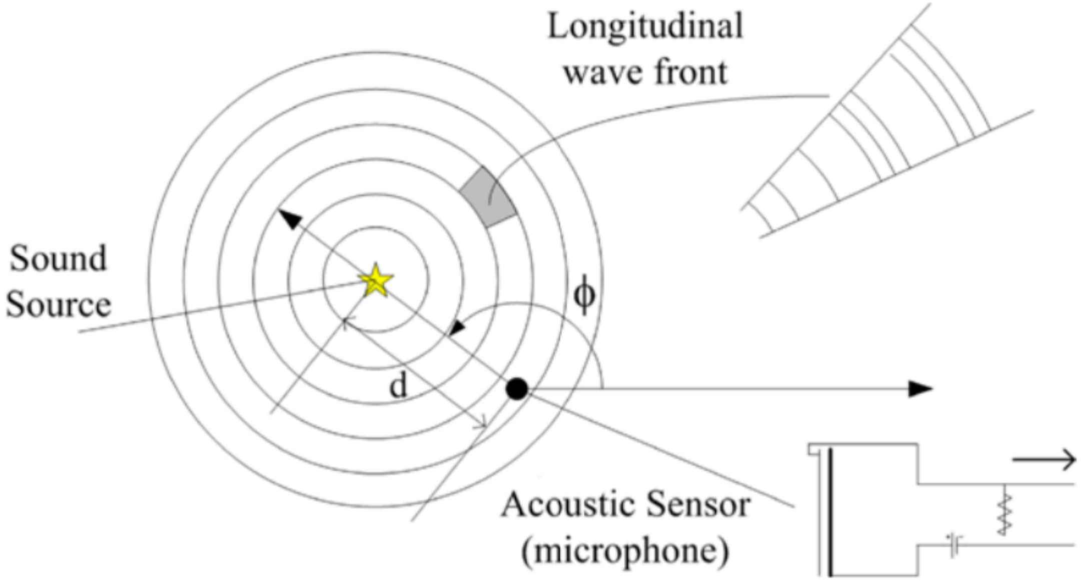
Sensor coverage models are mechanisms to measure sensors' sensing capability and quality.

SENSOR COVERAGE MODEL

Let us first consider an example of using an acoustic sensor to measure sound pressure.
The figure illustrates the radiation of sound waves from a sound source in the free space.
Suppose that the sound source emits a pure tone characterized by a sine function $a\, sin(2\pi f + \theta\,)$, where a is the maximum amplitude, f the frequency, and θ the initial phase.
The root−mean−square (RMS) amplitude

$$a_{\text{ams}} = \frac{a}{\sqrt{2}}$$

is used to measure the sound pressure



$$L_p = 20\log_{10} a_{\text{ams}} + C \text{ (dB)},$$

where the constant C is the reference sound pressure (an internationally agreed value of C is 94 dB)

COVERAGE MODEL

A free space is a homogeneous medium, free from boundaries or reflecting surfaces.

In a free space (a homogeneous medium, free from boundaries or reflecting surface, the sound waves radiated from a sound source will diffuse in all directions, and its amplitude (or energy in terms of arms) attenuates with distances.

The sound pressure at a given point, at a distance d (in meters) from the source, can be computed as

$$L_p = L_{\text{ref}} - 20\log_{10}\left(\frac{d}{d_{\text{ref}}}\right) \text{ (dB)},$$

where L_{ref} is the sound pressure at a reference point (usually greater than 1 meter to avoid source near field effects), and dref is the distance between the reference point and sound source.
From this expression it can be seen that in the free space, the sound pressure decreases by 6 dB when the distance d doubles.

RANGE LIMITATIONS

Sensors have limitations, and acoustic sensors are no exception. The measurable sound pressure has limit (in dB), beyond which an accurate measurement cannot be obtained.

The lower measurement limit of a microphone is established by its cartridge thermal noise.

There are two sources of thermal noise, air damping and preamplifier circuitry.

The air damping causes a white noise that is a property of the microphone.

The preamplifier has low–frequency noise which is inversely proportional to frequency and white noise.

The thermal noise determines the lower measurement limit of an acoustic sensor, which is the dB level that would be read by a measurement instrument connected to the microphone output when there is no acoustic pressure applied to the microphone.

If the distance between a sound source and an acoustic sensor is too large, the sound pressure at the sensor location is too small and cannot be accurately measured by the sensor.

This suggests that a sensor may only sense some object within a limited range. Or in other words, a sensor can cover some region with limited area.

SENSOR COVERAGE MODELS

Sensor coverage models measure the sensing capability and quality by capturing the geometric relation between a space point and sensors.

A sensor coverage model, often, can be formulated as a function of the Euclidean distances (and the angles) between a space point and sensors.

The inputs of such a coverage function are the distances (and angles) between a particular space point and sensors' locations, and the output is called *coverage measure* of this space point, which is a nonnegative real number.

The concept of coverage function can be introduced in the context of two-dimensional space.
Let us consider a space point z and a set of sensors $S = \{s_1, s_2, \ldots, s_n\}$.
Let $d(s, z)$ ($d(s, z) \geq 0$) denote the Euclidean distance between a sensor s and a space point:

$$d(s, z) \doteq \sqrt{(s_x - z_x)^2 + (s_y - z_y)^2}$$

in the two-dimensional space, where (s_x, s_y) and (z_x, z_y) are the Cartesian coordinates of the sensor s and the space point z, respectively.

SENSOR COVERAGE MODELS

The figure illustrates an example of a sensor covering a point in space.

$d_n = (d(s_1, z), d(s_2, z), \ldots, d(s_n, z))$ to denote the vector of such distances and

$\varphi_n = (\varphi(s_1,z),\varphi(s_2,z),\ldots,\varphi(s_n,z))$ to denote the vector of such angles between the set of sensors and the space point.

A sensor coverage model can be formulated as a coverage function f mapping (d_n,φ_n) to a nonnegative real number, that is,

$$f : (\boldsymbol{d}_n, \boldsymbol{\phi}_n) \rightarrow \mathbb{R}^+,$$

where $\mathbb{R}^+$ stands for the set of nonnegative real numbers.

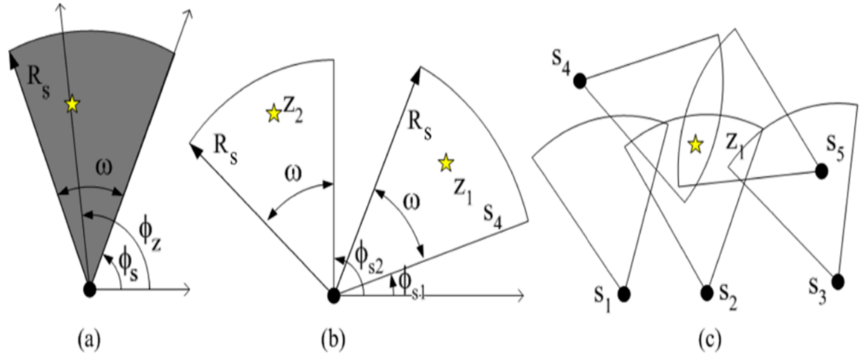


Fig. 2.2 Illustration of (**a**) a directional Boolean sector coverage model; (**b**) a directional Boolean sector coverage model with adjustable orientational angle; and (**c**) a space point being 3-covered by three sectors

$f(d_n,\varphi_n)$ *is* the coverage measure of the space point with respect to the sensors $s_1,s_2,\ldots,s_n$. Similar definition can also be applied in three-dimensional space yet with some simple modification of the definition of angles.

BOOLEAN SECTOR COVERAGE MODELS

The Boolean sector coverage model (sometimes called the sector model), which might be motivated from a directional camera, is a Boolean directional coverage model.

φ_s is called an *orientational angle*, ω is called a *visual angle* of the sector model, and R_s is called a *sensing range*. The coverage function of the sector model is given by

$$f(d(s,z),\phi(s,z)) = \begin{cases} 1 & \text{if } d(s,z) \le R_s \text{ and } \phi_s \le \phi(s,z) \le \phi_s + \omega, \\ 0 & \text{otherwise,} \end{cases}$$

where *d(s,z)* is the Euclidean distance between a sensor s and a space point *z*, and *φ(s,z)* is their angle.

This coverage function defines a sector: All space points within such a sector have the coverage measure of 1 and are said to be *covered* by this sensor.

All space points outside such a sector have the coverage measure of 0 and are said to be not covered by this sensor. The space point marked by a star has a coverage measure of 1 and is covered by the sensor.

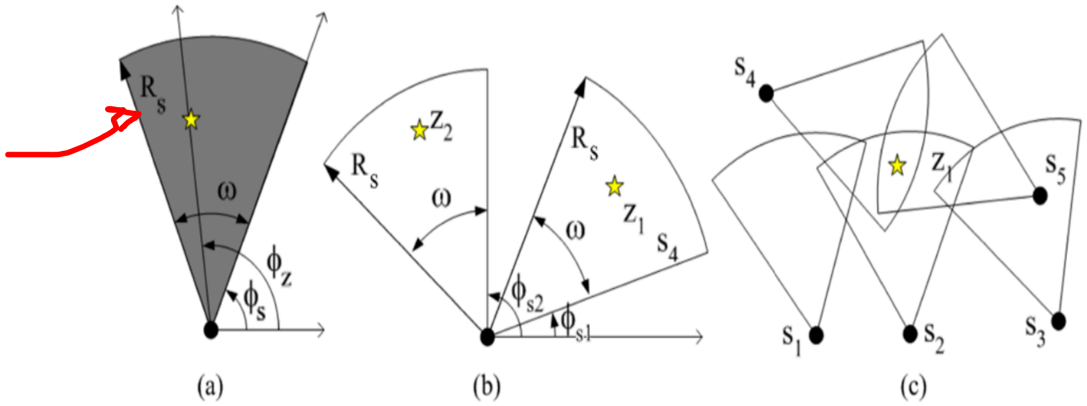


Fig. 2.2 Illustration of (**a**) a directional Boolean sector coverage model; (**b**) a directional Boolean sector coverage model with adjustable orientational angle; and (**c**) a space point being 3-covered by three sectors

BOOLEAN SECTOR COVERAGE MODELS

The orientational angle of a directional sensor might be adjustable after a sensor has been deployed.

The area that can be covered by such a sensor will be different when it takes different orientational angle.

For example, if the sensor takes φs_1 as its orientational angle, then the space point z_1 is covered, and z_2 is not.

If it takes φs_2 as its orientational angle, then the space point z_1 is not covered, and z_2 is covered.

A space point may be covered by more than one sector.

With the Boolean sector coverage model, the coverage measure of a space point relative to a set of sensors can be the addition of the coverage measure of the point relative to each individual sensor.

Formally, the coverage function can be defined as

$$f(\boldsymbol{d}_n, \boldsymbol{\phi}_n) = \sum_{i-1}^{n} f_i\big(d(s_i, z), \phi(s_i, z)\big),$$

where f_i is the coverage function of a sensor s_i.

- ✓ If $f(d_n, \varphi_n) = k$ $(k \geq 1)$, then we say that the point is *k-covered*.
- ✓ If a point is *k-covered*, it is also *(k − 1)*-covered. The figure illustrates an example of space point being *3-covered*, where the space point marked by the star is within the sensing sectors of sensors s_2, s_4 and s_5

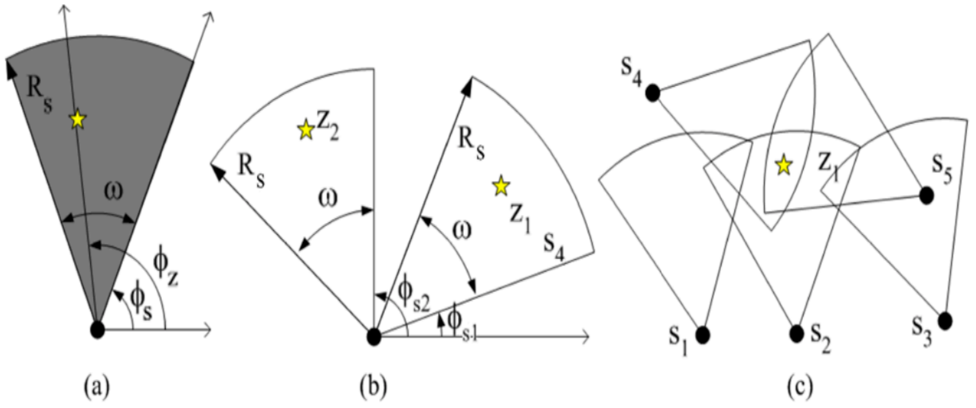


Fig. 2.2 Illustration of (**a**) a directional Boolean sector coverage model; (**b**) a directional Boolean sector coverage model with adjustable orientational angle; and (**c**) a space point being 3-covered by three sectors

BOOLEAN DISK COVERAGE MODELS

The Boolean disk coverage model (often simplified as the disk model) might be the most widely used sensor coverage model in the literature. The coverage function of the disk model is given by

$$f\big(d(s,z)\big) = \begin{cases} 1 & \text{if } d(s,z) \le R_s, \\ 0 & \text{otherwise,} \end{cases}$$

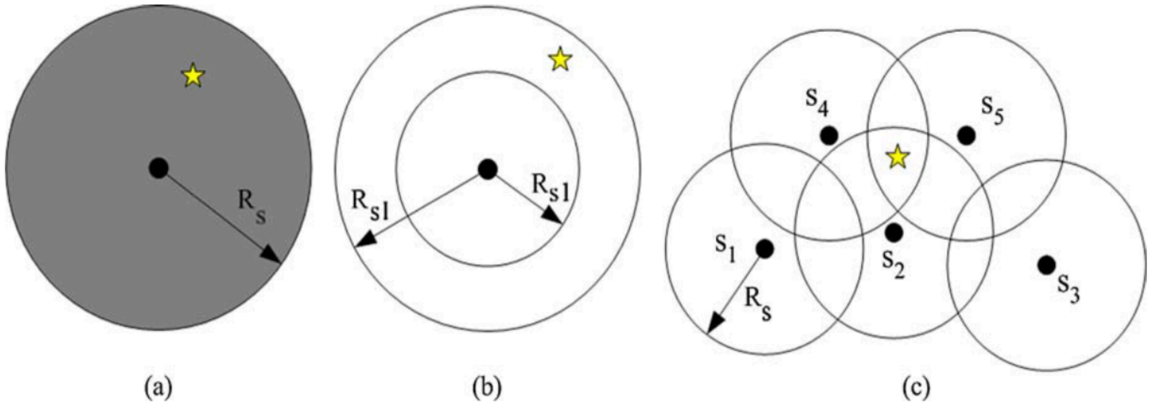


Fig. 2.3 Illustration of (**a**) an omnidirectional Boolean disk coverage model; (**b**) an omnidirectional Boolean disk coverage model with variable sensing ranges; and (**c**) a space point being 3-covered by three disks

where *d(s,z)* is the Euclidean distance between a sensor *s* and a space point *z*, and the constant Rs > 0 is called *sensing range*.

This function defines a disk (often called a *sensing disk*) centered at the sensor with the radius of the sensing range..

The disk coverage model is an omnidirectional coverage model.

All space points within such a disk have the coverage measure of 1 and are said *covered* by this sensor.

All space points outside such a disk have the coverage measure of 0 and are said not covered by this sensor.

BOOLEAN DISK COVERAGE MODELS

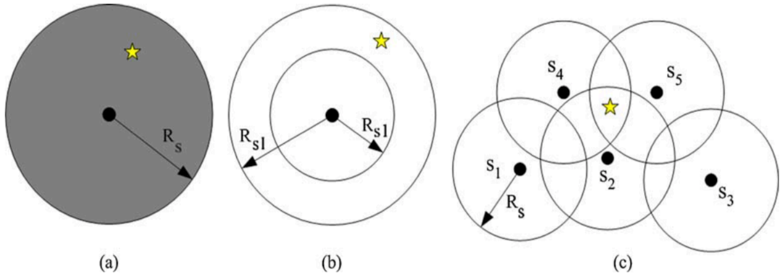


Fig. 2.3 Illustration of (**a**) an omnidirectional Boolean disk coverage model; (**b**) an omnidirectional Boolean disk coverage model with variable sensing ranges; and (**c**) a space point being 3-covered by three disks

The sensing range Rs is used to characterize the sensing capability of a sensor.

Different sensor types are assumed to have different sensing ranges.

Actually, one sensor may have different sensing ranges and can choose one sensing range as its working sensing range.

The space point marked by the star is not covered if the sensor that uses R_{s1} as sensing range; it is covered if the sensor uses R_{s2} as sensing range.

It is generally assumed that a sensor consumes more energy when it uses a larger sensing range.

A space point may be located within more than one sensing disks. Under the disk coverage model, the coverage measure of a space point relative to a set of sensors can be the addition of the coverage measure of the point relative to each individual sensor. Formally, the coverage function can be defined as

$$f(\boldsymbol{d}_n) = \sum_{i=1}^{n} f_i\big(d(s_i, z)\big),$$

where $f_i(\cdot)$ is the coverage function of a sensor s_i . If $f(d_n)=k$, then we say that the point is k-*covered*. Again, if a point is k-covered, it is also (k − 1)-covered. In the above figure a space point being 3-covered, where the space point marked by the star is within the sensing disks of sensors s_2, s_4, and s_5.

ATTENUATED DISK COVERAGE MODELS

The sensing quality of a sensor reduces with the increase of the distance away from the sensor.

An attenuated disk coverage model is used to capture such attenuated sensing qualities. An example of an attenuated disk coverage model is given by

$$f(d(s,z)) = \frac{C}{d^{\alpha}(s,z)},$$

where α is the path attenuation exponent, and C a constant.

Since it is a nonnegative function, a single sensor enforces its coverage measure to any point in the space.

The figure illustrates such an attenuated disk coverage model. The coverage measure of z_1 is larger than that of z_2, as it is closer to the sensor.

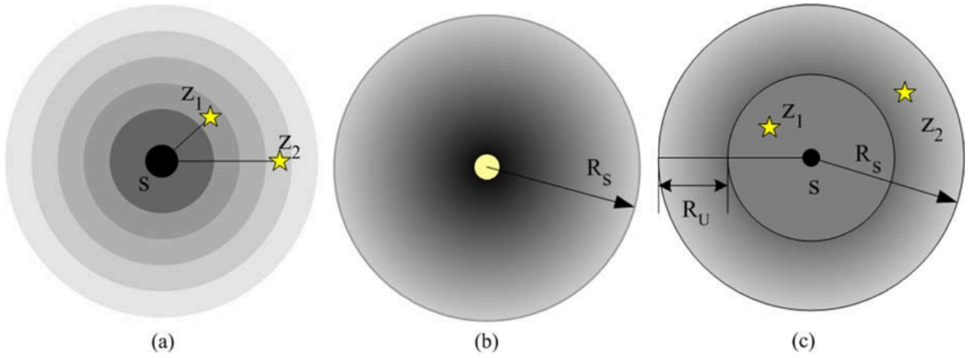


Fig. 2.4 Illustration of (**a**) an attenuated disk coverage model; (**b**) a truncated attenuated disk coverage model; (**c**) a truncated multilevel attenuated disk coverage model

ATTENUATED DISK COVERAGE MODELS

There may be more than one sensor in a sensor field.

Under the attenuated disk coverage model, the coverage measure of a space point relative to a set of sensors is the addition of the coverage measure of the point relative to each individual sensor.

Formally, the coverage function is modified as

$$f(\boldsymbol{d}_n) = \sum_{i=1}^{n} \frac{C}{d^{\alpha}(s_i, z)}.$$

In some cases, only the sensors close to a space point are included in the computation of the above equation for simplification.

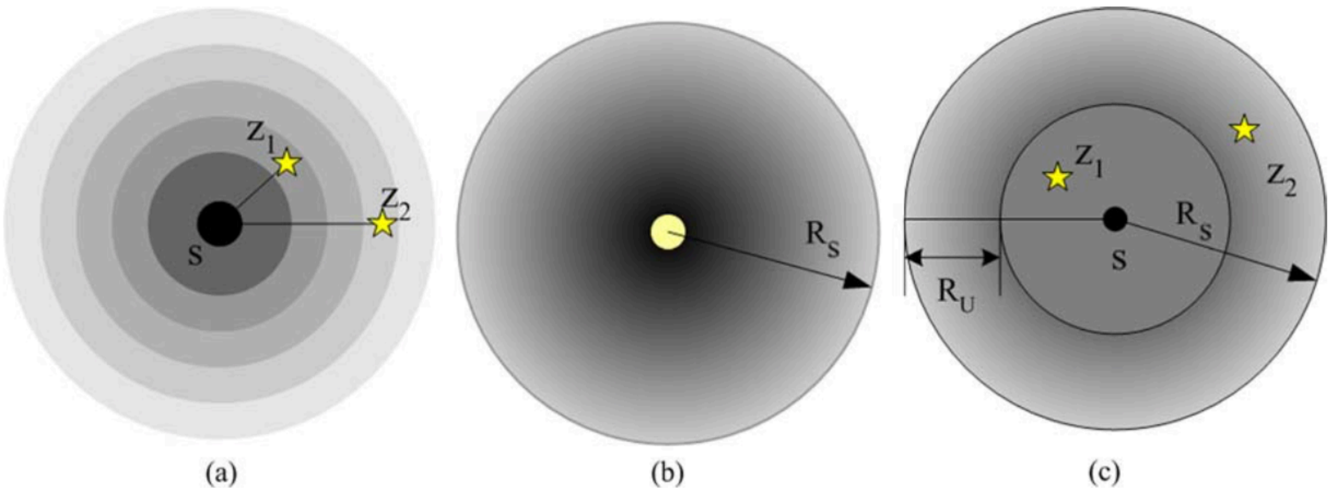


Fig. 2.4 Illustration of (**a**) an attenuated disk coverage model; (**b**) a truncated attenuated disk coverage model; (**c**) a truncated multilevel attenuated disk coverage model

TRUNCATED ATTENUATED DISK MODELS

In the attenuated disk coverage model, the coverage measure becomes very small when the distance between a space point and a sensor becomes very large.

In such cases, the coverage measure might be neglected, and some approximations can be made by truncating the coverage measure for larger values of distance:

$$f(d(s,z)) = \begin{cases} Ce^{-\alpha d(s,z)} & \text{if } d(s,z) \le R_s, \\ 0 & \text{otherwise,} \end{cases}$$

where α is a parameter representing the physical characteristics of the sensor unit, and Rs the sensing range.

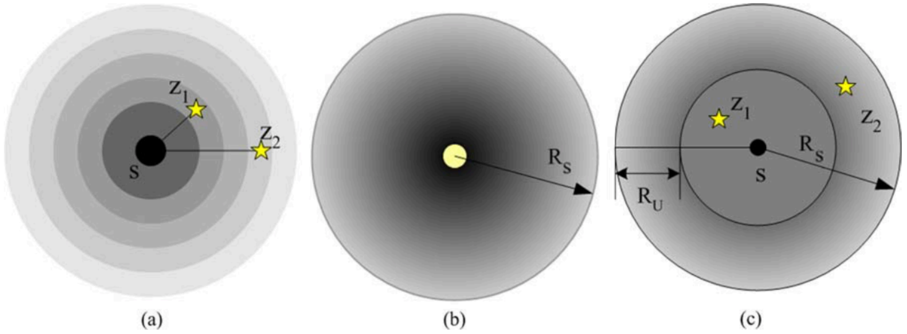


Fig. 2.4 Illustration of (**a**) an attenuated disk coverage model; (**b**) a truncated attenuated disk coverage model; (**c**) a truncated multilevel attenuated disk coverage model

Another truncated attenuated disk model is defined as follows:

$$f(d(s,z)) = \begin{cases} 1 & \text{if } d(s,z) \le R_s - R_u, \\ e^{-\alpha(d(s,z)-(R_s-R_u))^{\beta}} & \text{if } R_s - R_u < d(s,z) \le R_s, \\ 0 & \text{if } R_s < d(s,z), \end{cases}$$

where Rs is the sensing range, Ru is called the uncertain range, and α and β are constants.

The use of R_u is to capture the reduction but not yet the vanishing of the sensing quality when the distance between a sensor and a space point increases.

The relation between the coverage measure and sensor–point distance for the aforementioned disk coverage models, is depicted in the figure.

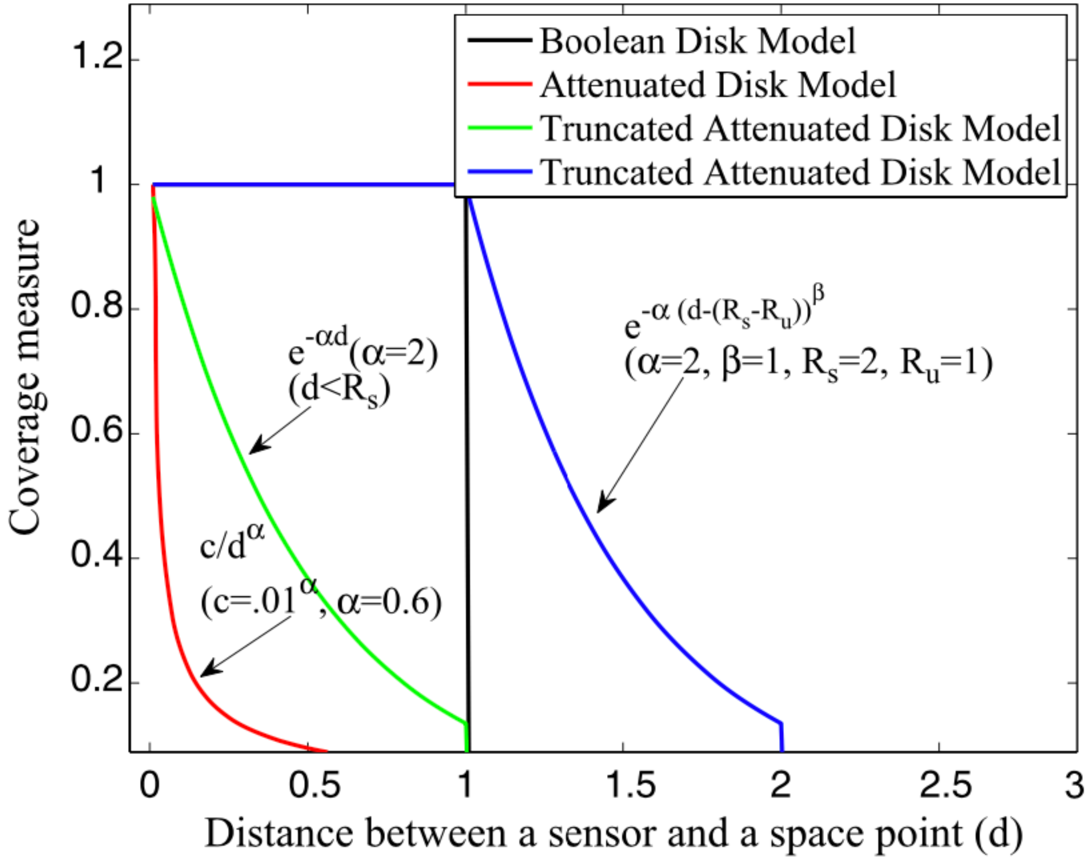


Fig. 2.5 Illustration of the relation between the coverage measure and sensor–point distance for (**a**) Boolean disk coverage model;
(**b**) attenuated disk coverage model; and (**c**) and (**d**) truncated attenuated disk coverage model

DETECTION COVERAGE MODELS

An important application of sensor networks is to detect some event occurred at some location.

In the context of detection application, the sensing quality of a sensor can be represented by its detection probability.

The detection probability of a space point by a single sensor is also related to, among other factors, the distance between them.

However, the detection probability of a space point relative to a set of sensors is no longer simply computed as the addition of the detection probability of the point relative to each individual sensor (otherwise, it might be larger than one).

Instead, a *value fusion* or *decision fusion* can be used to derive the detection probability.

Consider a general signal propagation model where the signal parameter θ (e.g., the sound pressure of a sound source) attenuates along with the signal propagation. Depending on the hypothesis of whether the target is present (H_1) or not (H_0), the readings at the sensor s_k are given by

$$H_0 : x_k = n_k,$$

$$H_1 : x_k = \frac{\theta}{d_k^\alpha} + n_k,$$

where α is the attenuation exponent, d_k^α is the Euclidean distance between the sensor s_k and the space point z, and n_k is the measurement noise (e.g., circuity thermal noise). It is often assumed that the noise follows a Gaussian distribution with zero mean and variance σ^2_k, denoted by $N(0,\sigma^2_k)$.

DETECTION COVERAGE MODELS

Given the threshold A, a sensor makes its detection decision of whether a target is present by

$$x_k \underset{H_0}{\overset{H_1}{\gtrless}} A.$$

That is, if the measurement is larger than A, it decides that a target is present, and if the measurement is less than A, it decides that a target is not present.

When a target is present at the space point z, the detection probability P_k^d of the sensor s_k is given by

$$P_k^d = \Pr\left[\frac{\theta}{d_k^\alpha} + n_k \geq A\right] = Q\left(\frac{A - \frac{\theta}{d_k^\alpha}}{\sigma_k}\right),$$

where $Q(\cdot)$ is the Q-function defined by

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}}\, dt.$$

Since Q-function is a decreasing function, the detection probability P_k^d decreases when the distance d_k increases.

DETECTION COVERAGE MODELS

We define a threshold for detection probability, P_{th}^d, and only

those points with detection probability equal to or larger than such a threshold,

i.e. $P_k^d \geq P_{\text{th}}^d$, are considered as covered by this sensor,

It is actually, the truncated attenuated disk coverage model.

If we do not discriminate the points with detection probability not less than the detection threshold and simply call these points being covered by the sensor, then finally we get a Boolean disk coverage model.

In such a case, the points with the detection probability equal to the threshold consist of a circle, and their distances to the sensor are also equal and often regarded as the sensing range R_s . That is,

$$Q\left(\frac{A - \frac{\theta}{R_s^\alpha}}{\sigma_k}\right) = P_{\text{th}}^d \quad \Longrightarrow \quad R_s = \left(\frac{\theta}{A - \sigma_k Q^{-1}(P_{\text{th}}^k)}\right)^{\frac{1}{\alpha}},$$

where $Q^{-1}(\cdot)$ denotes the inverse function of $Q(\cdot)$

When K sensors are used to cooperatively detect an event, the value fusion technique can be used to compute the detection probability of a space point by these sensors.

DETECTION COVERAGE MODELS

Let x_k, $k = 1,2,...,K$, denote the readings of the kth sensor.

Compare the sum of x_k and a threshold to make a decision whether or not a target is present.

We assume that all the noises n_k ($k = 1,2,...,K$) are independent Gaussian noises with zero mean and variance σ^2 .
When a target is present at the space point z, the detection probability by these sensors is given by

$$P_K^d = \Pr\left[\sum_{k=1}^{K}\left(\frac{\theta}{d_k^\alpha} + n_k\right) \geq \sqrt{K}A\right] = Q\left(\frac{\sqrt{K}A - \sum_{k=1}^{K}\frac{\theta}{d_k^\alpha}}{\sqrt{K}\sigma}\right),$$

$\sqrt{K}A$ is the value fusion threshold. Again, we can use the threshold of detection probability P_{th}^d, and the points with detection probability not less than the detection threshold are called covered by these sensors.
In such a case, the covered points by K sensors satisfy the following distance inequality

$$\sum_{k=1}^{K}\frac{1}{d_k^\alpha} \geq \frac{\sqrt{K}}{R_s^\alpha},$$

where d_k is the distance between a point and a sensor s_k, and R_s . This equation defines a Boolean detection model for K sensors, that is,

$$f(\boldsymbol{d}_K) = \begin{cases} 1 & \text{if } \sum_{k=1}^{K}\frac{1}{d_k^\alpha} \geq \frac{\sqrt{K}}{R_s^\alpha}, \\ 0 & \text{otherwise.} \end{cases}$$

DETECTION COVERAGE MODELS

This figure marks out the space points that are considered as being covered when (α = 1.0) as the coverage model.

The points within a disk are considered as being covered when only one sensor is used.

They are also considered as being covered when more than one sensor is used.

Furthermore, those points colored by yellow (and outside the disks) are not covered by only a single sensor but are considered as being covered by more than one sensor.

These additionally covered space points can be regarded as a kind of cooperation gain by using more than one sensor for the same sensing task

There are also many decision fusion techniques that can be used to derive the detection probability by a set of sensors. For example, the following decision fusion computes the overall detection probability by a set of sensors:

$$P_K^d = 1 - \prod_{k=1}^{K}(1 - P_k^d),$$

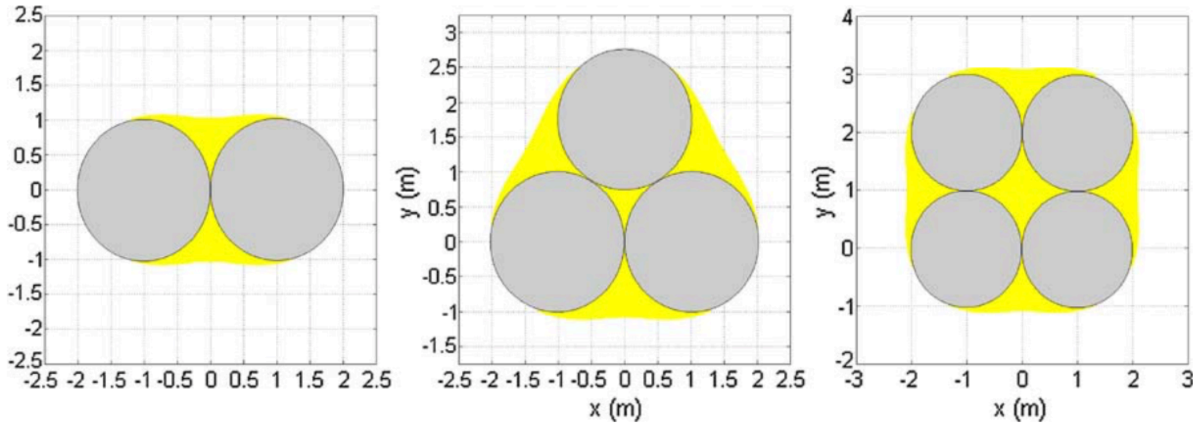


Fig. 2.6 Illustration of the space points covered by using the detection coverage model of (**a**) 2 sensors, (**b**) 3 sensors, and (**c**) 4 sensors (for the color version, see Color Plates on p. 208)

Note that this depends on the distance between a sensor and the space point. This It is called the *probabilistic coverage* in some papers . Again, we can set a threshold and define that a point is covered by K sensors ($s_1, \ldots, s_K$) if its overall detection probability is not less than such a threshold.

DETECTION COVERAGE MODELS

Another commonly used decision fusion technique is the *majority voting*.

Assume K sensors, each independently making a local binary decision δ_k .

If $x_k \geq A$, then a sensor decides that a target is present, and $\delta_k = 1$; otherwise, a sensor decides that a target is not present, and $\delta_k = 0$.

Note that δ_k is dependent on the distance between a sensor and a space point. The consensus decision rule is given by

$$\sum_{k=1}^{K} \delta_k \underset{H_0}{\overset{H_1}{\gtrless}} \left\lceil \frac{K}{2} \right\rceil.$$

That is, if more than a half of sensors decide a target being present, then the overall decision fusion result is that a target is present; otherwise, the final result is that a target is not present. The consensus detection probability hence is given by

$$P_K^d = \Pr\left[\sum_{k=1}^{K} \delta_k^d \geq \left\lceil \frac{K}{2} \right\rceil\right] = \sum_{j=\lceil \frac{K}{2} \rceil}^{K} \sum_{\text{permutation}} \prod_{k=1}^{j} P_k^d \prod_{k=j+1}^{K} (1 - P_k^d),$$

The second sum term is to add up the product of detection probabilities and missing probabilities over all possible permutations over k. this equation can also be used to define a coverage model.

Also, we can set a threshold and define that a point is covered by K sensors (s_1 , . . . , s_K) if its overall detection probability is not less than such a threshold.

ESTIMATION COVERAGE MODELS

Another important application of sensor networks is estimating signal parameters.

In the context of estimation application, the sensing quality of a sensor can be represented by its estimation errors.

The estimation error of a space point by a single sensor is also related to, among other factors, the distance between them.

However, when multiple sensors are used in estimation, the estimation error of a parameter of some signal at a space point is no longer simply computed as the addition of the estimation error of the point relative to each individual sensor.

Assume that a signal occurs at some space point z and that its signal parameter θ attenuates along with the signal propagation.
For example, θ can be the acoustic amplitude due to a motor engine or due to a leakage of gas barrel.

For magnetic wave such as acoustic wave, its amplitude is attenuated when propagating. The measurement of the signal parameter by a sensor s_k is given by

$$x_k = \frac{\theta}{d_k^{\alpha}} + n_k,$$

where α is the attenuation exponent, $d_k^{\alpha} = d^{\alpha}(s_k, z)$ is the Euclidean distance between the sensor s_k and the space point z, and n_k is the measurement noise (e.g., circuity thermal noise).

ESTIMATION COVERAGE MODELS

It is often assumed that the noise follows a Gaussian distribution with zero mean and variance σ_k^2, denoted by $\mathcal{N}(0, \sigma_k^2)$.

A parameter estimator can be used to estimate θ based on the measurements x_k k=1,2,…..,K

Let θ and $\tilde{\theta} = \hat{\theta} - \theta$ denote the estimate and the estimation error, respectively.

If the estimation error is small, the estimate of the signal parameter is obtained with high confidence level.

We can use the probability that the absolute value of the estimation is less than or equal to a predefined constant A, i.e.,

$$\Pr[|\tilde{\theta}_K| \leq A]$$

to measure how well a point is monitored $\Pr[|\tilde{\theta}_K| \leq A]$ is called the *information exposure*).

Some standard estimators can be used to perform the estimation. For example, if the *best linear unbiased estimator* (BLUE) is used, the estimate $\hat{\theta}_K$ is given by

$$\hat{\theta}_K = \frac{\sum_{k=1}^{K} d_k^{-\alpha} \sigma_k^{-2} x_k}{\sum_{k=1}^{K} d_k^{-2\alpha} \sigma_k^{-2}},$$

ESTIMATION COVERAGE MODELS

and the estimation error θ_K is given by

$$\tilde{\theta}_K = \frac{\sum_{k=1}^{K} d_k^{-\alpha} \sigma_k^{-2} n_k}{\sum_{k=1}^{K} d_k^{-2\alpha} \sigma_k^{-2}}.$$

If we further assume that all noises have the same variances, i.e., $\sigma^2_k = \sigma^2$ for all $k = 1, 2, \ldots, K$, then we have

$$\Pr[|\tilde{\theta}_K| \leq A] = 1 - 2Q\left(\frac{A}{\sigma}\left(\sum_{k=1}^{K} d_k^{-2\alpha}\right)^{\frac{1}{2}}\right),$$

We can see that depending on the distances between the K sensors and the space point and can be used as a coverage function to define an estimation coverage model.

ESTIMATION COVERAGE MODELS

Now let us consider that only one sensor is used in estimation:

$$\Pr\left[|\tilde{\theta}_k| \leq A\right] = 1 - 2Q\left(\frac{A}{\sigma} d_k^{-\alpha}\right).$$

Since Q(·) is a decreasing function, $\Pr[|\tilde{\theta}_K| \leq A]$ decreases as the distance d_k increases.

Furthermore, if we define a threshold ε (0 ≤ ε ≤ 1) and if only the points with $\Pr[|\tilde{\theta}_K| \leq A]$ equal to or larger than such a threshold, i.e., $\Pr[|\tilde{\theta}_K| \leq A] \geq \varepsilon$, are considered as covered by this sensor, then we actually define a truncated attenuated disk coverage model.
If we do not discriminate the points within such a disk, then finally we get a Boolean disk coverage model. In such a case, the points with $\Pr[|\tilde{\theta}_K| \leq A] = \varepsilon$ consist of a circle, and their distances to the sensor are also equal and can be regarded as the sensing range R_s . That is,

$$1 - 2Q\left(\frac{A}{\sigma R_s^{\alpha}}\right) = \epsilon \quad \Longrightarrow \quad R_s = \left(\frac{A}{\sigma Q^{-1}(\frac{1-\epsilon}{2})}\right)^{\frac{1}{\alpha}},$$

where $Q^{-1}(\cdot)$ denotes the inverse function of Q(·).

ESTIMATION COVERAGE MODELS

We can also define a Boolean estimation coverage model of K sensors by comparing $\Pr[|\tilde{\theta}_K| \leq A]$ with the threshold ε . In such a case, the covered points by K sensors satisfy the following distance inequality:

$$\sum_{k=1}^{K} \frac{1}{d_k^{2\alpha}} \geq \frac{1}{R_s^{2\alpha}},$$

where d_k is the distance between a point and a sensor s_k, and R_s .
Thus equation defines a Boolean estimation coverage model for K sensors (which is called the *information coverage* model), that is,

$$f(\boldsymbol{d}_K) = \begin{cases} 1 & \text{if } \sum_{k=1}^{K} \frac{1}{d_k^{2\alpha}} \geq \frac{1}{R_s^{2\alpha}}, \\ 0 & \text{otherwise.} \end{cases}$$

32 2 Sensor Coverage Model

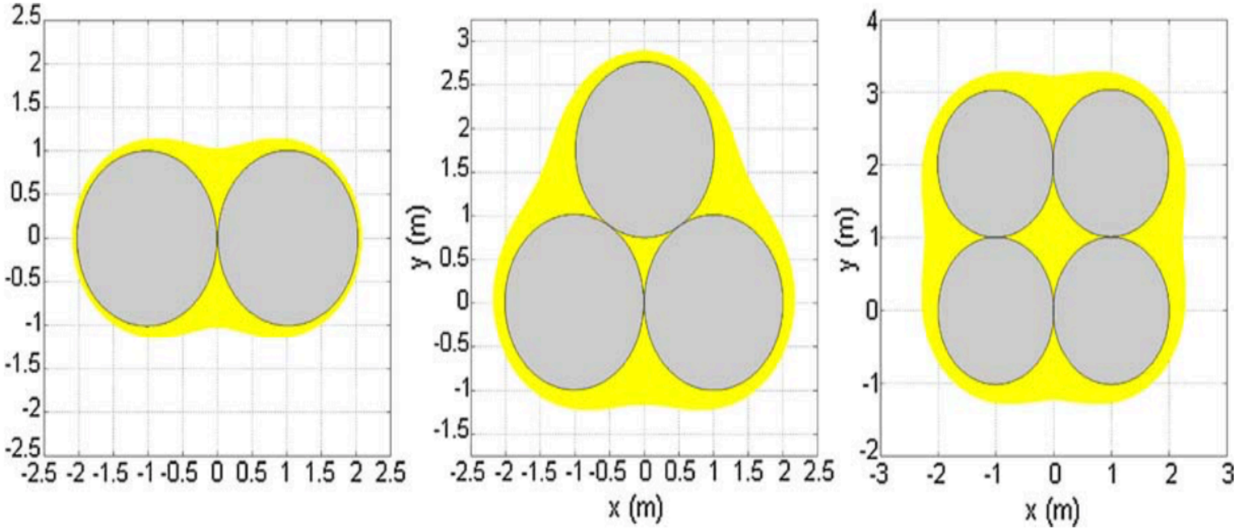


Fig. 2.7 Illustration of the space points covered by using the estimation coverage model of (**a**) 2 sensors, (**b**) 3 sensors, and (**c**) 4 sensors (for the color version, see Color Plates on p. 208)

ESTIMATION COVERAGE MODELS

The figure marks out the space points that are considered as being covered when ($\alpha = 1.0$) as the coverage model.

It is also seen that when using more than one sensor for the same sensing task (estimation in this case), the covered space points are more than those by only using one single sensor.

Again, the increased coverage area can be seen as a kind of cooperation gain.

32 2 Sensor Coverage Model

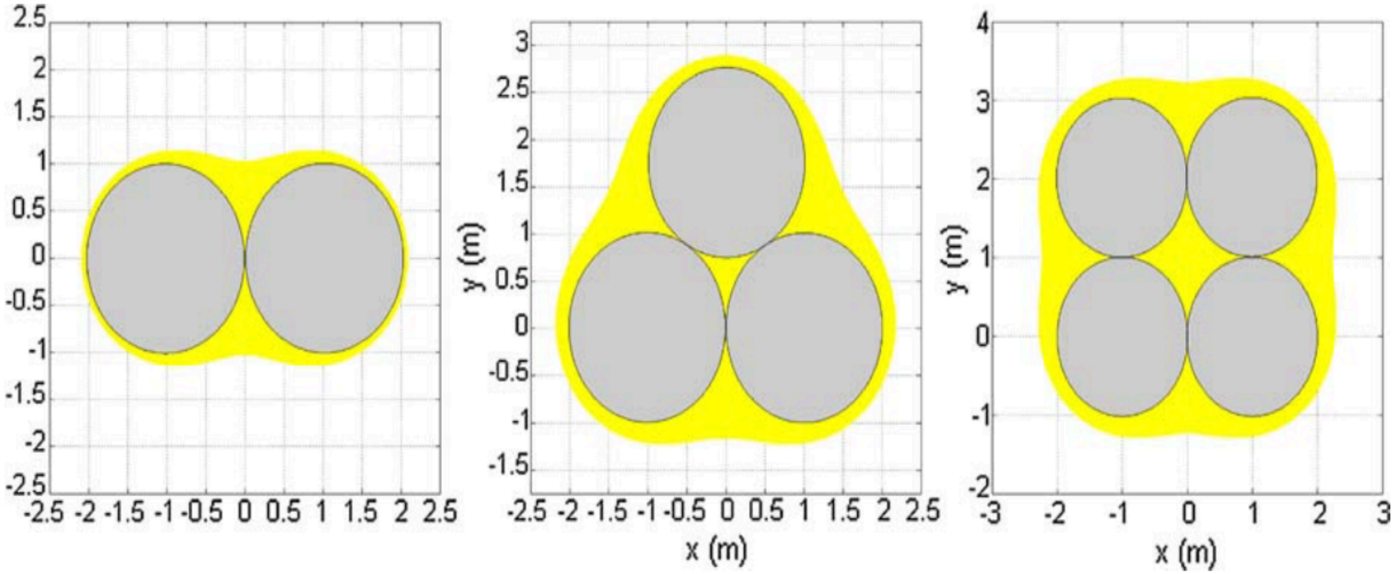


Fig. 2.7 Illustration of the space points covered by using the estimation coverage model of (**a**) 2 sensors, (**b**) 3 sensors, and (**c**) 4 sensors (for the color version, see Color Plates on p. 208)

SENSOR NETWORK COVERAGE CONTROL

NETWORK COVERAGE

Sensor coverage model can be considered as a measure of the sensing capability and quality of individual sensors.

Network coverage, on the other hand, can be regarded as a collective measure of the quality of the service provided by a network of sensors nodes at different geographical locations.

A sensor that is performing the sensing task and is covering some space points consumes energy to generate sensing data.

In order to reduce data volume and prolong network lifetime, it is much necessary to control which sensors to sense and for how long.

Network coverage control, as one of the *middleware services* in the protocol stack, serves such a functionality. According to different application scenarios, network assumptions and operation objectives, the problem of network coverage control can be formulated and solved in many different approaches.

NETWORK COVERAGE

Network coverage can be used to refer to the coverage relation between field-wide points and network-wide sensors.

Sometimes, we may regard network coverage as a collective measure of the quality of service provided by a network of sensor nodes at different geographical locations.

The sensor unit of a sensor node, which is to perform the sensing task and to produce sensing data, is controllable to be active or inactive (sleep).

An active sensor node consumes energy to generate sensing data, and an inactive (sleep) sensor node does not generate any sensing data. We use *network coverage control* to refer to the network-wide control of individual nodes' sensor unit.

The fundamental motivation of network coverage control, which is also its ultimate objective, can be boiled down to the *energy efficiency*.

A sensor node, which is normally designed for some specific sensing task (e.g., sensing temperature, acoustic, or seismic signals), is in general with small size, low weight, and limited (and non-rechargeable) battery energy.

NETWORK COVERAGE

The temperature and relative humidity sensor MEP510 by Crossbow Technology Inc. is of size (cm) $6.35 \times 4.13 \times 3.81$ and weight (grams) 89.8 including a battery.

The expected lifetime of a MEP510 is 6 months when default sampling rate is used.

A network consisting of sensor nodes with limited and nonrechargeable power supplies cannot perform the required sensing task if all or a fraction of sensor nodes have used up their energy.

Therefore, in order to conserve energy and prolong network lifetime, we need to control which sensor to be active (to cover some space points) and for how long.

A sensor which is performing some sensing task will produce its sensing data at some sampling rate.

The sensing data may be first processed locally within the sensor node, and only the results are sent back to the sink.

Sometimes, all the sensing data may need to be transmitted to the sink.

The straightforward benefit of coverage control is to reduce the volume of sensing data while still guaranteeing the quality of the sensing task.

Other consequent benefits from the reduced network traffic also include the reduced power consumption for data transmission, the reduced transmission collisions, and the reduced data delivery delay

NETWORK COVERAGE CONTROL

Consider the two sensor networks used to cover one target and transmit the sensing data back to the sink.

Suppose that each sensor node has one energy unit, which can be used to produce two units of data in two time units.

Assume that transmitting one unit of data to the sink consumes 0.5 unit of energy.

Then sensor node s_1 (s_2) has lifetime of one time unit: It consumes one energy unit to produce one unit data in one unit and send it back to the sink.

If we use s_1 and s_2 to cover the target simultaneously, then the network traffic is two units of data in one unit time, and the total network lifetime is only one time unit.

On the other hand, if the quality of service is not affected by allowing only one sensor to monitor the target, then we can let sensor node s_1 to operate for one time unit and sensor node s_2 to operate for another one time unit.

With such a control of target coverage, the network traffic is only one unit of data in one unit time, and the network lifetime can be extended to two time units

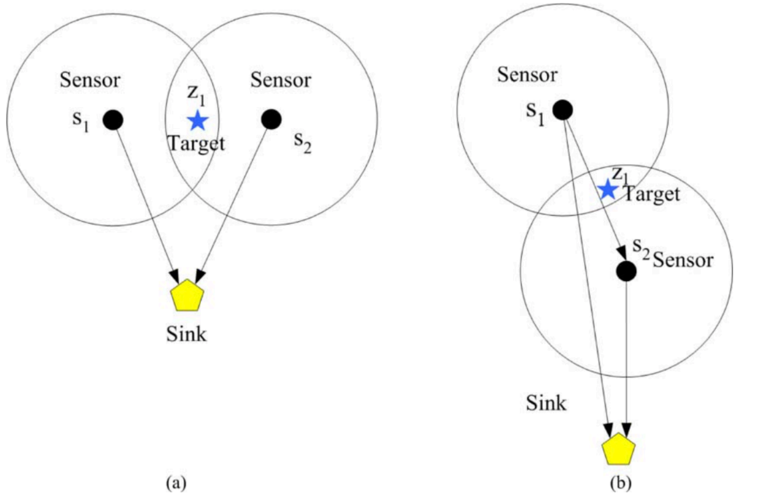


Fig. 3.1 Illustration of benefits from network coverage control in **(a)** a single-hop network; and **(b)** a multi-hop network

Sometimes, network coverage control also incorporates insight in the routes selection. The sensor node s_1 can use single-hop transmission to send its data to the sink directly or use multi-hop transmission by using sensor node s_2 as its relay to transmit its data to the sink.

When the sensor s_1 is used to cover the target, we also need to decide which route it should use to transmit its data.

The energy consumption of the individual sensors and the whole network heavily depends on the route selection.

Furthermore, if we use sensor s_1 and s_2 sequentially to perform sensing task, we also need to decide how long that sensor is used to cover the target and how much sensing data it can produce.

NETWORK COVERAGE

Coverage control not only can be applied to those already deployed networks for prolonging network lifetime but also can be used before network deployment.

The study of the network coverage control can help reducing network setup costs.

For small-scale networks where sensor nodes can be manually placed at the desired locations, network coverage control often refers to deciding where are the optimal locations to place the sensor nodes, such that the quality of the sensing task can be guaranteed and the network cost can be minimized.

For large-scale networks where sensor nodes are normally randomly scattered within the sensor field, network coverage control usually refers to determining the minimum number (cost) of sensor nodes to provide the required coverage requirements.

As a short summary, the motivations and objectives for network coverage control can be summarized as to reduce network setup costs, conserve node energy consumption, and prolong network lifetime while guaranteeing the specified coverage requirements.

COVERAGE CONTROL IN THE PROTOCOL ARCHITECTURE

Network coverage control is achieved by controlling individual nodes' sensor unit in a network–wide way.

In order to implement network coverage control, it is necessary to equip each single sensor node with a *coverage control module*, which is a software implementation of coverage control algorithms to instruct the activation and deactivation of its sensor unit.

COVERAGE CONTROL IN THE PROTOCOL ARCHITECTURE

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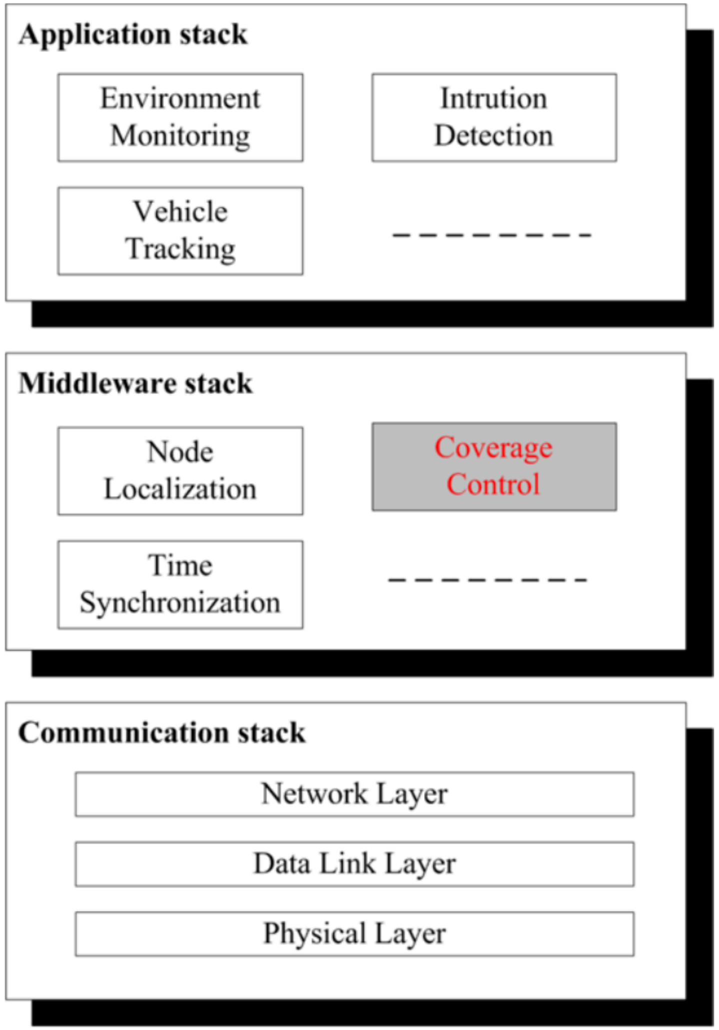
Where this control take place?



The coverage control is often constructed as a middleware modules that sits above the communication protocol stack and below the application stack.

COVERAGE CONTROL IN THE PROTOCOL ARCHITECTURE

The coverage control module provides the sensing unit activation and deactivation service to applications.

For example, if a surveillance application only requires that each area is monitored by one active sensor, then the coverage control module is to schedule the least number of active sensors to satisfy this surveillance requirement.

The coverage control module uses the services provided by the network layer via an interface. For example, after the coverage control module has decided to become active, it may need to inform its neighbors its decision.

This can be done by passing a message to the network layer, and the network layer decides where to send such a message.

On the other hand, the network layer also passes the related messages that is received from other nodes to the coverage control module. Indeed, message exchange is essential in the implementation of distributed and localized algorithms.

Sometimes, we can also consider a cross-layer design by combining the coverage control module and the network layer: We not only schedule the activation and deactivation of nodes' sensor unit but also select the routes for each active sensor node to send its data back to the sink.

The coverage control module may also use the services from other middleware modules. For example, when it is to decide whether its covered area can also be covered by its active neighbors,

it may need the location information for the area coverage computation. In a round-robin manner of coverage decision and maintenance, different nodes may need to synchronize their new round of coverage control, which uses the services provided by the time synchronization module.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

The fundamental objective of network coverage control is to conserve energy; however, different coverage control problems can be formulated according to application scenarios, node capabilities, network assumptions, and performance metrics. In this section, we discuss some design issues of network coverage control.

Coverage Type: Coverage type refers to the subject to be covered by a sensor network. Coverage in sensor networks can be classified into three types, namely, *point* (*target*) *coverage*, *area coverage*, and *barrier coverage*.

Area coverage problem, equally treats every point in the sensor field and addresses the problem of how to efficiently cover the whole sensor field. Barrier coverage is different from point coverage and area coverage in that the subjects to be covered are not known before node deployment.

Instead, it concerns with constructing a barrier for intrusion detection or finding a penetration path across the sensor field with some desired property.

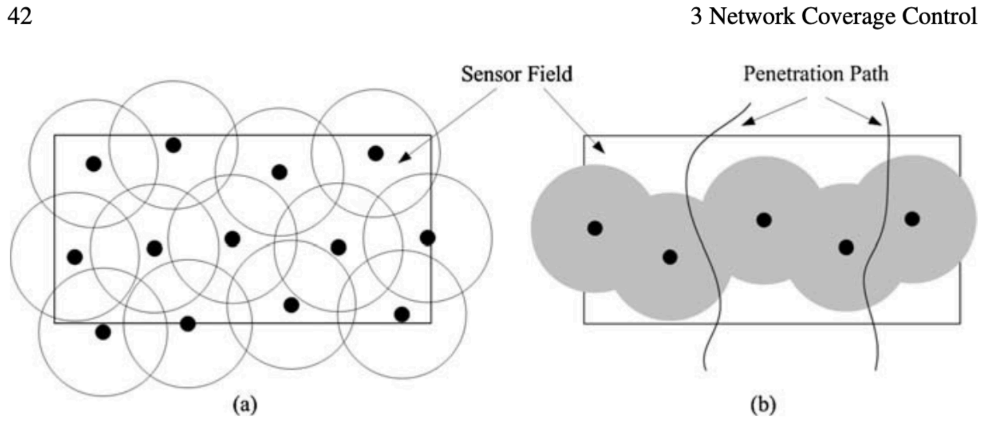


Fig. 3.3 Examples of (**a**) area coverage and (**b**) barrier coverage

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Deployment Method: Deployment method concerns with how a sensor network is constructed.

In general, a sensor network can be constructed by deterministically placing sensor nodes at desired locations or by randomly scattering sensor nodes into the sensor field.

In deterministic sensor deployment, the common objective is to place the least number of sensor nodes (the minimum network setup cost) to achieve the application coverage requirement. Deterministic sensor placement can be applied to a small to medium sensor network in a friend environment.

When the network size is large or the sensor field is remote and hostile, random sensor deployment might be the only choice. There are two commonly used random deployment models: One is the *random uniform deployment* of N sensor nodes such that each node has equal likelihood of falling at any location in the sensor field, independently of the other nodes.

The other is the *random Poisson deployment* with density λ, where the process for deploying sensor nodes is a stationary Poisson point process, and the number of sensors in any subregion is Poisson distributed and mutually independent of each other in different disjoint subregions [6]. In the random deployment;

An interesting question is: what is the minimum number of sensor nodes that need to be scattered so that complete coverage can be achieved. This is the *critical sensor density* problem.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Node Heterogeneity: Node heterogeneity refers to that sensor nodes have different sensing, processing, or communication capabilities. In other words, sensor nodes are heterogeneous.

For example, some sensor nodes are resource rich nodes with more power supply or are equipped with better sensing, processing, and communication units.

In the context of sensing disk coverage model, some sensors may cover a disk with larger radius than other sensors'.

A heterogeneous sensor network may also consist of both stationary or mobile sensor nodes. Stationary sensor nodes will be fixed on its location once deployed, and mobile nodes can move around after the initial deployment. A mobile node is in general more expensive than its stationary compeers and is normally assumed to be resource rich.

Many network performance metrics can be greatly improved by using a few of mobile nodes. In the context of network coverage, mobile nodes can be used to heal coverage hole that is not covered by any stationary sensor or to maximize area coverage by relocating mobile sensor nodes.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Activity Scheduling: Activity scheduling is to schedule the activation and deactivation of nodes' sensor units.

In a randomly deployed sensor network, the scattered sensor nodes may be more than the optimum.

If the area covered by one sensor can also be covered by other sensors, such a sensor can be as redundant and can be temporarily transited into the energy saving sleep state.

Hence the objective of activity scheduling is to decide which sensors to be in which states and for how long time, so that application coverage requirement can be guaranteed and network lifetime can be prolonged.

In the context of coverage problems, *network lifetime* is often defined as the period from the network setup time to the time that the deployed network cannot provide adequate coverage (e.g., the coverage ratio less than a predefined threshold).

Many *distributed algorithms* and *centralized algorithms* for activity scheduling have been proposed based on different assumptions and objectives.

In the distributed algorithms, the decision process is localized in each individual sensor node, and only information from neighboring nodes is used for the activity decision.

In centralized algorithms, a central controller makes all decisions and distributes the results to sensor nodes. For large sensor networks with dynamic topologies, distributed algorithms are more preferred than centralized ones.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Coverage Degree: Coverage degree describes how a point is covered.

For example, in the sensing disk coverage model, coverage degree refers to how many sensors cover a point. A point is called k−covered if it is within k distinct sensors' coverage disks. Using more than one sensor to cover a point can improve coverage robust− ness. If a point is covered by k sensors, then it can tolerate up to $k - 1$ failed sensors.

A similar definition can also be applied to other coverage models. For the sake of simplicity, in the whole book, by a covered point we mean that this point is covered by at least one sensor. We will explicitly state higher coverage degree when necessary. Coverage degree is considered as one of the application coverage requirements to be observed by coverage control algorithms.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Coverage Ratio: Coverage ratio measures how much area of a sensor field or how many targets satisfy the application requirement of coverage degree.

For example, if eight out of ten targets are covered, then the coverage ratio is 80%.

We sometimes use *complete coverage* to refer to 100% coverage ratio, that is, every point within a sensor field (or every target in the target set) achieves the required coverage degree.

Similarly, we use *partial coverage* to state the situation that not all points in the sensor field (or not all targets in the target set) can be covered with the required coverage degree.

Complete area coverage is a very strict requirement, which normally requires a large amount of sensors to be deployed into the sensor field. Instead of asking for 100% coverage ratio, we may allow that some points or targets are not covered and trade–off the coverage ratio with less active sensors.

Coverage ratio is often regarded as one of the application coverage requirements to be observed by coverage control algorithms.

DESIGN ISSUES OF NETWORK COVERAGE CONTROL

Network Connectivity: Network connectivity concerns with how to guarantee that all sensor nodes can find a route to the sink.

Although normally this is the task of the network layer, it may also be incorporated into the design of coverage control algorithms as a cross–layer approach.

In wireless sensor networks, wireless sensor nodes communicate via their radio transceivers.

Two wireless nodes are directly connected if they can transmit and receive the data to and from each other via radio channel. Two nodes can also be connected by multi–hop transmissions with some other nodes serving as *relays*. A connected network ensures that the sensing data of any sensor node can be transmitted to other nodes and the sink, possibly via multi– hop transmissions.

A commonly used transmission model is the disk model where a node can communicate with other nodes within a disk centered at itself with the radius of its *communication range*. In such a case, a unit disk graph can be used to describe the network. Some other transmission model also allows variable transmission powers and hence variable transmission ranges, and allows transmission errors.

The transceiver unit is in general independent of the sensor unit in a sensor node, and the sensing range and the communication range of a sensor can be with different distances.

The design of sensor activity scheduling can be coupled with the network connectivity, and we will study some examples of such cross–layer activity scheduling algorithms in the later chapter. Network connectivity sometimes is also considered as one of the application coverage requirements to be observed by coverage control algorithms.

COVERAGE PERFORMANCE METRICS

Performance Metric: Performance metrics are used to compare different coverage control algorithms. For example, if two activity scheduling algorithms can achieve the same level of coverage degree and coverage ratio, the one selects a fewer number of nodes is often considered as the better one.

Furthermore, with different problem settings, the performance metrics can be different for different coverage problems.

The most commonly used performance metric is to use the least number of sensor nodes to achieve application coverage requirements or, on the other hand, to achieve the maximum coverage when giving a fixed number of nodes.

Some other performance metrics include the coverage lifetime which is the maximum time to ensure application coverage, the coverage intensity which is defined as the average time ratio between covered and uncovered period for a point, the movement cost which is used to compare movement strategies, and so on. Sometimes, network connectivity, though independently controlled by radio transceiver, is also used as a performance metric for activity scheduling.

A TAXONOMY FOR NETWORK COVERAGE CONTROL PROBLEMS IN SENSOR NETWORKS