Chapter 1

Introduction to Wireless Sensor Networks

1.1 Wireless Sensor Networks: Overview

Wireless Sensor Networks (WSNs) have drawn significant attention of the research community in the last few years, because of the rapid advancement in wireless communications, networking and digital electronics devices. The miniaturization of computing and sensing technologies enables the development of tiny, low-power and inexpensive sensors, actuators, and controllers. WSNs generally contain a large number of low-cost, low power and multifunctional sensor nodes that have limited sensing, computing and communication capabilities. A sensor network is designed to sense the event of interest, collect and process the data, and transmit the sensed information towards the sink as shown in figure 1.1. Sensor nodes when properly networked and programmed can be useful in sensing the event in the hostile environment where human intervention is not possible [1].

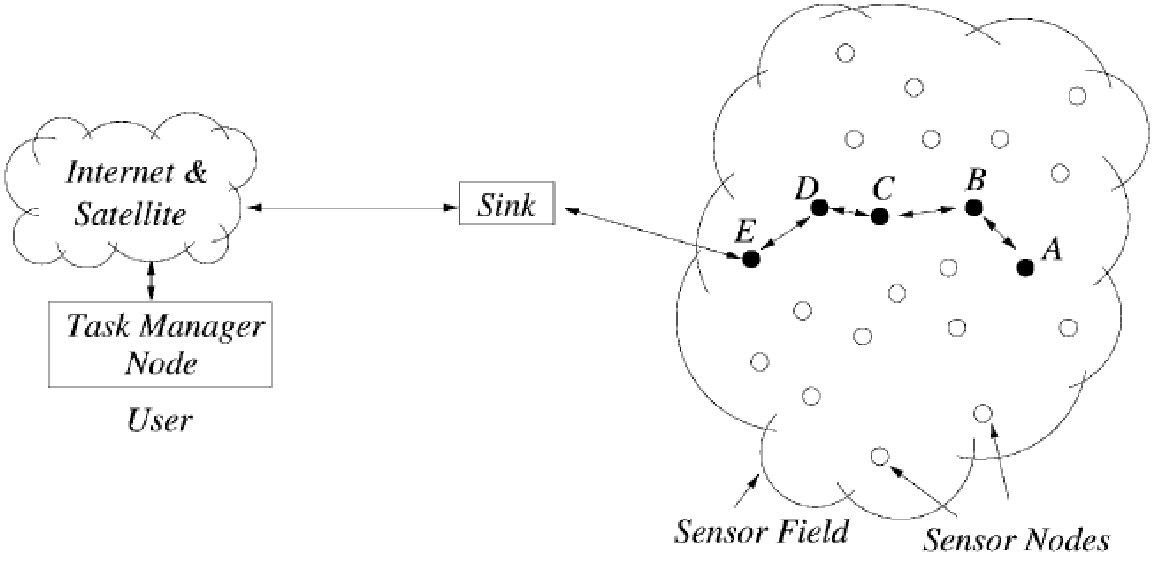


Fig. 1.1 Scenario of Wireless Sensor Networks

Sensing is a technique used to collect information regarding physical events if there is a change in the phenomenon of events, such as an increase in temperature, pressure, humidity etc. A physical object accomplishing such type of sensing task is termed as a sensor. There are different types of sensors developed for different application for example position can be estimated by Global Positioning System (GPS) sensors, ultrasound-based sensors, infrared-based sensors. Similarly information such as sound and smell can be sensed by microphones and piezoelectric resonators. Sensors may be static or mobile [2]. The smaller size, lighter in weight, and mobility features are unique characteristics of a sensor and make WSNs useful in several applications

1.2 Sensor Node Architecture

Architecture of a sensor node and its major component are illustrated in Fig. 1.2. A sensor node has five basic components: Sensing Unit, Controller, Memory Unit, transceiver unit, power unit and some additional components such as location finding System [3,4].

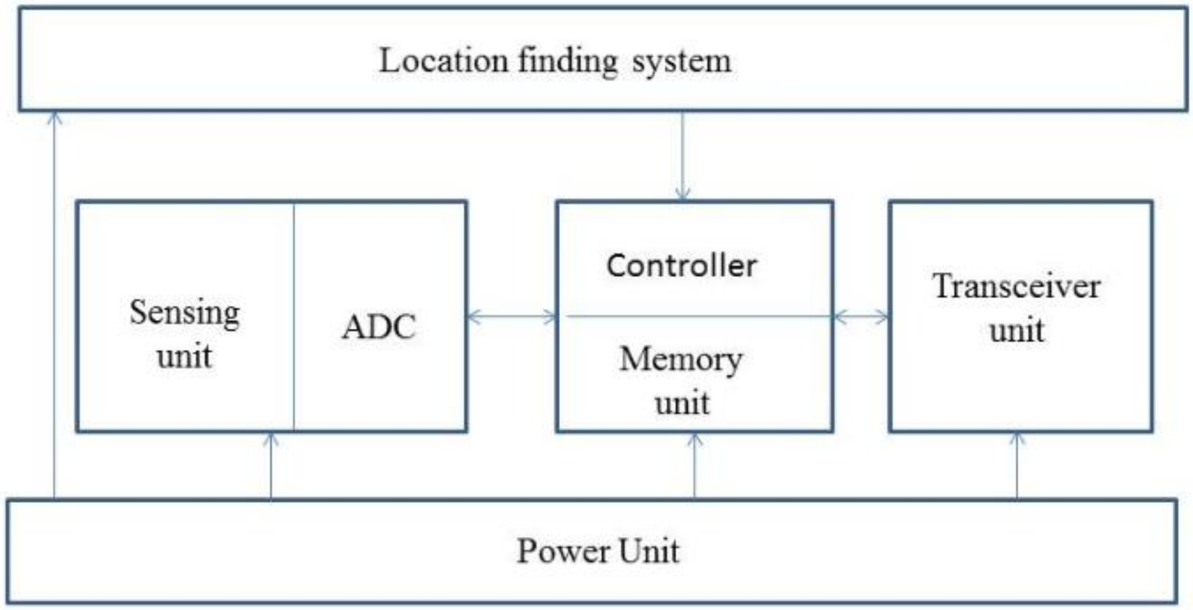


Fig. 1.2 Hardware Architecture of a Sensor Node

1.2.1 Controller

The controller is a primary component of a sensor node. Its main task is to collect data from all other sensor nodes, process the data and decide to forward it. The controller also controls the functionality of the other components in the sensor node.

1.2.2 Memory unit

The memory component is basically used to store intermediate data or program instructions in random access or read only memory.

1.2.3 Transceiver Unit

The communication device is used to interchange data between individual nodes. This device comprises short range radio transceiver. A transceiver is a device that has a aggregated transmitter and receiver in one unit.

1.2.4 Sensing Unit

A sensor is a hardware component that generates a signal when there is a change in the physical condition of the environment such as temperature, humidity, pressure. Because of power constraint the sensor is tiny in size and has low data rate sensing capability.

1.2.5 Power Supply

In a sensor node, power supply is one of the most important components. Generally each component in the sensor node is powered by battery. The main consumption of energy is done by communication, sensing and data processing. Therefore, due to limited battery power, each component must operate in an energy efficient manner.

1.3 Application of WSN

WSNs have different types of sensors such as seismic, magnetic, thermal, visual, infrared, acoustic, and radar. These types of sensor can monitor different environmental conditions such as temperature, humidity, pressure, speed, direction, movement, noise levels, mechanical stress levels and presence or absence of certain kind of objects [1, 4, 5]. As a consequence, a wide variety of applications are possible.

1.3.1 Military Applications

Wireless Sensor Networks can be an integral part of military command, control, communications, computing, intelligence, surveillance and targeting systems. Sensitive objects like atomic plants, gas pipeline, and ammunition depot can be protected with the help of Wireless Sensors Networks. Vibration and magnetic sensors can trace the movement of intruders who try to penetrate the area which is under surveillance.

1.3.2 Environmental Monitoring

Wireless Sensor Networks can be used to detect environmental conditions such as volcano monitoring, in which seismic and acoustic sensors collect seismic and infrasonic signals. Wireless Sensor Networks are deployed in many cities to watch over the vividness of harmful gases for peoples. Weather forecasting, forest fire and flood can be detected early by densely deployed sensor nodes.

1.3.3 Health Monitoring

Various health care applications were projected for Wireless Sensor Networks. WSNs are used in hospitals for tracking and monitoring patients, doctors, drug executives and all medical resources. Body temperature, sugar level, blood pressure can be measured by Wireless Sensor Networks and further they can communicate the sensed data to doctor for medical prescription.

1.3.4 Habitat Monitoring

A project is made to study the movement pattern of zebras in Africa; this project is named as "The Zebranet Project". Researchers of colleges of the Atlantic and the Intel Research Laboratory, Berkeley have developed The Great Duck Island project to study the behaviour of Storm Petrel on Great Duck Island, Maine [6].

1.3.5 Home Application

Smart home system can be built by using Wireless Sensor Networks. Sensor networks allow user to monitor their homes remotely, such as switch off or on lights, monitoring sleeping baby from remote location etc.

1.4 Issues of Sensor Networks

WSN design is motivated and influenced by several challenging application areas. In this section, we outline several issues involved in the design and development of wireless sensor networks [1, 2, 5].

1.4.1 Ad hoc Deployment

A large number of WSN applications do not have information about the locations where sensor nodes are to be deployed. This is particularly important for hostile regions where human intervention is not possible. As an example, sensors observing the battlefield or disaster zones may be thrown from aircraft over the area of interest. Therefore, nodes deployed randomly in remote location have to establish communication with neighbouring sensor nodes, identify their location, configure, synchronize and calibrate by themselves. Autonomous functioning of nodes in the network is therefore, an important design issue.

1.4.2 Energy Efficiency

The sensors are battery powered with limited energy capacity. Replacement of these batteries in the field is not feasible. Major part of energy of a sensor is generally consumed in communication with neighbours, sensing and processing but some part of energy is also drained in idle listening and overhearing. Therefore, this energy resource must be properly utilized to prolong the lifetime of the network.

1.4.3 Scalability

WSNs are generally consists of hundreds or sometime thousands of nodes. The routing protocol and algorithms are required to be scalable with the number of nodes. As the number of nodes increases the complexity of the algorithm and routing protocol should not increase. Similarly, as the number of nodes increase, the storage space of network should increase, and the communication cost of the system should not rise.

1.4.4 Fault tolerance

Malfunctions in WSNs are caused by many factors. First, sensor node may fail due to battery exhaustion or damage by external physical attacks. Additionally, node may gather and communicate inaccurate reading due to harsh environmental conditions. Second, links are failure-prone due to external object or environmental conditions, causing network partition and dynamic changes in network topology. Third, due to large number of nodes, congestion may occur and result in packet loss. Robustness to sensor and link failure must be achieved through redundancy, and collaborative processing and communication. Therefore, with fault tolerance, failure of sensor nodes does not affect the overall performance of WSNs.

1.4.5 Coverage and Connectivity

The main objective of sensor deployment is to keep the track of a field and report the collected information to the sink for further processing. For a sensor network to operate successfully, sensors must maintain both coverage and network connectivity. Due to constraint of limited sensing and communication range, the issue of coverage and connectivity in wireless sensor networks becomes a challenge. Therefore, maximizing coverage as well as maintaining network connectivity using the resource constrained nodes is the extremely important problem. This issue is rigorously analyzed in this dissertation.

1.4.6 Data Aggregation

As sensor nodes are densely deployed, they may generate correlated redundant data. Since sensor nodes are energy constrained, therefore it is necessary to reduce this redundant data at intermediate nodes. Data aggregation is the process of aggregating the data received from multiple sensors to reduce redundant data and provide high quality information to the base station. This technique helps in reducing energy of sensor nodes and latency of network.

1.4.7 Latency

Latency is defined as the time elapsed between sensing an event of interest and receiving of this information at the sink. Some application of sensor networks are time critical, therefore it is crucial to receive data on time. Sensors are energy constrained and to save energy the radio of redundant sensors are kept in sleep mode. In active mode, a node can receive and transmit data. While in the sleep mode, it turns off its radio to save energy. Therefore, a node should always be conscious of its neighbour’s awaken time, because data cannot be transferred until both the transmitter and the receiver are active. Therefore, long delay caused by processing or communication is usually not acceptable.

1.5 Problem Definition

In our research work, we have proposed to study coverage and connectivity using deterministic and probabilistic sensing and communication models. Further, to achieve high accuracy and fault tolerance we proposed to develop a model for k-coverage and q-connectivity. To make the model more realistic we planned to use log normal shadowing path loss model and its effect on coverage and connectivity.

1.6 Thesis Organization

Chapter 1 has already described an introduction to Wireless Sensor Networks. This chapter discusses overview of network, sensor node architecture, application of WSNs, and various issues regarding WSNs. Coverage and Connectivity is one of them.

Chapter 2 describes the basic concepts of Coverage, types of coverage, design issues, sleep scheduling and network connectivity.

Chapter 3 presents all the mathematical analysis of coverage and connectivity under channel randomness.

Chapter 4 presents all the results and Performance Analysis.

Finally chapter 5 contains conclusion and Future Work.

Chapter 2

Coverage and Connectivity in WSN

Coverage and Connectivity are two most fundamental and important research issues is sensor networks and over the year have been studied intensively by the researchers. Coverage and Connectivity problem is a measure of Quality of Service in Wireless Sensor Network. The coverage problem determines how well each point in the area of monitoring region is covered by the sensors. A set of deployed sensor nodes is said to be connected if there is at least one path between each pair of sensor nodes in the network. To maximize the coverage, the sensors cannot be placed very far from each other to avoid coverage holes. At the same time they cannot be placed very closer to each other since it increases redundancy without achieving any extra coverage. On the other hand, to guarantee connectivity, sensors should be placed close enough to ensure that they are within the communication range of each other [7, 8, 9]. Sensor nodes have limited sensing and communication capability. Therefore, maintaining both coverage and connectivity is very crucial and challenging issue in WSN.

2.1 Coverage in WSN

Given a set of sensors $S = \{s_1, s_2, \dots \dots s_N\}$ in a two dimensional area where each sensor $s_i (i = 1,2, \dots \dots N)$ is located at (x_i, y_i) and has a sensing radius r_s. Any point in the 2-D monitoring region is said to be covered if it is in the sensing radius of at least one sensor node as shown in Fig. 2.1. Based on application, coverage can be classified into three classes, area coverage, target coverage and barrier coverage [10].

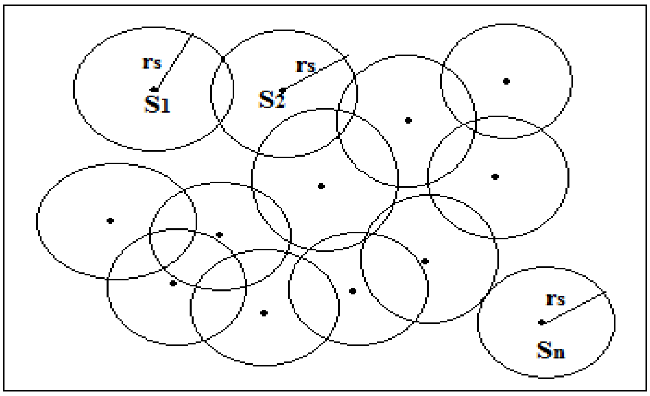


Fig. 2.1 Coverage in Wireless Sensor Networks

2.1.1 Area Coverage

In area coverage, a set of sensors is distributed in the monitoring region to monitor the given area. In the area coverage problem the goal is to monitor each point of the region of interest with minimal number of sensor nodes. If each point is covered by at least k different working sensor nodes, the area is said to be k- covered.

2.1.2 Target Coverage

Target coverage is the term used for monitoring a limited number of predetermined targets in the region of interest. This type of coverage is more suitable for military surveillance. The requirement of target coverage is that each target must be monitored continuously by one or more sensors, provided that every sensor has the capacity to monitor all targets within its sensing range.

2.1.3 Barrier Coverage

Barrier coverage refers to the detection of movement across a barrier by sensor. A strip area with a sensor network deployed over it is considered to be barrier protected, if each and every crossing track through the strip is protected by sensor network. There are several applications of barrier coverage such as deploying sensors on the battlefield to detect illegal intruder, to detect the spread of deadly chemicals, etc.

2.2 Design Issues

There are various issues that need to be considered when designing an approach for coverage and connectivity in a sensor network.

2.2.1 Node Deployment

Node deployment algorithm help to maximize the coverage area, increase connectivity, and extend the lifetime of network. Perfect node deployment may not just prevent the node redundancy to reduce the network costs, but it can also extend the lifetime of the network. Sensor nodes are deployed in the field either by placing them properly in the predetermined locations (deterministic deployment) or by throwing randomly in the hostile or harsh environment (random deployment). In deterministic deployment better coverage and maximum network lifetime can be achieved with minimal number of sensor nodes. In random deployment, sensor nodes are deployed densely into the field randomly. Once the nodes are deployed, network is left unattended for monitoring and for further processing. In random deployment, maintaining coverage and connectivity could be difficult and challenging task. Random node deployment in 2-D monitoring region can exhibit different type of distribution such as Gaussian distribution, Poisson distribution etc. Gaussian distribution or normal distribution has different detection capabilities at different locations of monitoring region in WSNs. But in Poisson distribution detection capabilities are same in all directions in the monitoring area. In our research work, we have used Poisson distribution. Randomly deployed sensor nodes are generally modelled by a Poisson point process with node density λ. Let N nodes are distributed according to Poisson point process over the area A. The probability that there is k number of sensor nodes located in an area A can be given by

$$P\left(N = k\right) = \frac{e^{-\lambda\|A\|}\left(\lambda A\right)^{k}}{k!} \tag{1.1}$$

Where $\|A\|$ is the size of area A.

2.2.2 Sleep Scheduling

Sleep scheduling is a technique in which sensor node is allowed to walk into sleep state when it is neither sensing nor passing on any information to other sensor node. For better coverage and connectivity dense deployment is crucial in harsh environment. In a dense network, interference may occur since many nodes communicate simultaneously. Sleep control may eliminate this issue by controlling the number of active nodes. Flipping active and inactive sensors is a technique to control the sensor and to prolong the lifetime of network [11]. Whenever a sensor node is in sleep state, it totally shuts itself down, leaving a single low-power timer on the wake by itself later. The objective of sleep scheduling scheme is to turn off redundant sensor nodes to help reduce energy consumption [12].

2.2.3 Adjustable Coverage Radius

Energy is an important resource in sensor network. Energy is consumed mainly due to communication or sensing activities performed by the sensor nodes. Energy can be saved if communication or sensing activities are used only up to desired level. Sensors which are having large sensing radius increases energy cost because it will require more advance filtering and signal processing techniques to improve the SNR. In many existing networks it is assumed that the sensing range of a sensor is fixed. However, adjusting the sensing range of wireless sensor is another power saving techniques. Therefore, with adjustable radii, the sensing energy can be saved.

2.3 Network Connectivity

A network of sensor is said to be connected only when there may be at least one path between each pair of sensor node in the network. It is essential to obtain ceaseless connectivity in a WSN after the sensor nodes are deployed in a harsh environment [13]. Connectivity in the WSNs is mainly affected by failure of sensor nodes, blockage of communication and topology changed due to movement of sensor nodes. For preventing sensor nodes from getting totally isolated from each other, high node density is necessary. Connectivity failure during the network operation is a biggest issue because disconnected network may be unable to communicate with the base station and thus sensed information cannot be transmitted. An approach to rebuild network connectivity is to remove the failed sensor nodes and replace them with additional new nodes to overcome the connectivity problem [14]. But in some applications, such as battlefield, redeployment of sensor nodes is not possible. Therefore, algorithm must be wisely designed to overcome the problem of connectivity.

Chapter 3

Coverage and Connectivity under Channel Randomness

3.1 Introduction

Coverage and connectivity had attracted the attention of researchers working in the designing of WSN. Some applications of WSN require k-coverage and q-coonectivity to make the system more fault tolerance and reliable. In most of the works in this area binary disk model of the channel propagation is used. Therefore, randomness and irregularity present in radio communications because of various environment effects are not considered. In this chapter, we are representing k-coverage and q-connectivity model for WSNs. In these models, we are using Poisson distribution for the node deployment. To make these models more realistic we are using path loss model with log normal shadowing to capture radio irregularities and also studied its effect on k-coverage and q-connectivity. The value of k and q can be different for different application.

3.2 System Model

In the system model, it is assumed that sensors are deployed randomly in the 2-D desired sensing area. These sensor nodes are deployed according to a homogeneous Poisson distribution with high density λ. A node with radius r_{max} can cover up a circular area πr_{max}^2 while neglecting the border effect. A sensor node finds the event of concern and sends this to the center (sink). We consider that all the nodes are fitted with transmitter and receiver having the same characteristics. So we are having a single value of range of sensing for all the sensor nodes. Still, the sensing range of every node depends on fixed value of transmission power P_s, and propagation loss because of distance and environment. Every sensor is aware of its location applying some localization methods [15]. System parameters and their definitions are named in Table 3.1.

Parameter	Definition
N	Number of sensor nodes
Λ	Node density
P_s	Transmission power of a sensor node
η	Path loss exponent
d_o	Close in reference distance
σ	Standard deviation
P_{senst}	Sensing sensitivity of sensor node
$\boldsymbol{\gamma}$	Threshold of received signal
A	Area of interest
r_{max}	Effective sensing range
P_{det}	Probability of detection of event

Table 3.1: Parameters definitions

3.2.1 Sensing Model

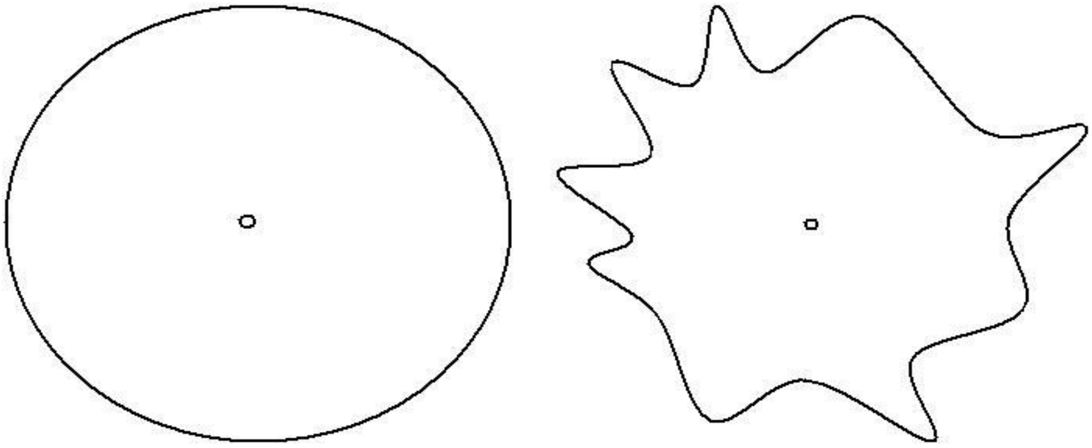
Sensing coverage is in general modeled by a binary disk model. It is assumed a sensor has circular sensing area so that it senses in all direction uniformly. A sensor node observes an event of interest existing in its sensing range with probability 1 and with probability 0 otherwise. The target point can be detected by the sensor s if $d(s, p_t) \le r_{\max}$. Depending on whether the event is inside the sensing range, the coverage function of the disk binary model is developed as the sensing function ((s, p)), as

$$f\left(d\left(s, p_t\right)\right) = \begin{cases} 1 & \text{if } d\left(s, p_t\right) \le r_{\max} \\ 0 & \text{if } d\left(s, p_t\right) > r_{\max} \end{cases} \tag{3.1}$$

In the function, $\mathrm{d}(s, p)$ is the distance between a point p_t and sensor node s and $r_{\max}$ is sensing range of the node. Fig. 3.1(a) depicts the transmission orbit of binary disk model which we have assumed to be isotropic. In comparison to binary sensing model, Probabilistic sensing model is much more realistic. The event detection probability of a sensor node is dependent on the event-sensor distance. As the distance between event and sensor increases, the sensed signal strength may drop along the path. For probabilistic sensing model, sensing function $f\left(d\left(s, p_t\right)\right)$ is modelled as

$$f\left(d\left(s, p_t\right)\right) = \begin{cases} 1 & \text{if } d\left(s, p_t\right) \le r_u \\ e^{-\alpha\left(s, p_t\right)^{\beta}} & \text{if } r_u < d\left(s, p_t\right) \le r_{\max} \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

Here α and β are sensor-dependent parameters representing the physical features of the sensor, r_u is the uncertainty starting point in the detection, and $r_{\max}$ is the maximum executable sensing range of the node. In real networks, obstacles, radio fluctuations and noise cannot be ignored and they cause randomness in the signal strength. This effect is known as shadowing. Due to shadowing random attenuation occurs in the network which is modeled as log-normal. This log-normal shadowing is the most widely taken model that considers shadowing effect. This model depicts that average signal strength received is decreasing logarithmically with respect to the distance between receiver and transmitter. Hence, due to shadowing effect and distance, the sensing ability is not alike in all the directions.



(a) **(b)**

Fig. 3.1(a) Transmission Range for ideal case (b) Transmission Range for effect of path loss & shadowing

3.2.2 Log-Normal Shadowing Path Loss Model

This model is representing the radio propagation in real natural world. Path loss is because of dissipation of the radiated power from the transmitter and the effects of shadowing. In this model, both propagation models (theoretical and measurement-based) suggest that the average of power of received signal reduces logarithmically with the distance [16]. In the path loss model of radio propagation, path loss corresponding to distance d is given as

$$PL(d) = PL(d_0) + 10\eta \log(d / d_0) + X_\sigma \tag{3.3}$$

Where $PL(d_0)$ is the path loss corresponding to a reference distance d_0, η denoted the exponent of path loss that shows the rate of increasing path loss with distance, and X_σ is a Gaussian random variable with mean value as zero and standard deviation σ expressing log-normal shadowing effect. The values of η and σ are calculated from measured data. In this model it is assumed that path loss, when measured, has same value in different direction. Though, it is experimentally shown by Zhou et al. [17] that path losses should be non-isotropic due to many factors such as transmitting power, signal-to-noise ratio, receiver sensitivity, antenna gain, and obstacle existing in the environment. So based on the experiment of [17], path loss expressed in (3.3) follows

DOI (Degree of irregularity)-adjusted path loss $\left(PL(d)_{DOI}\right) = path$ loss $PL(d) \times k_i$ (3.4)

Where $k_i = \begin{cases} 1 & \text{if i=0} \\ k_{i-1} \pm rand \times DOI & \text{if i<360 and i} \in \text{N} \end{cases}$

Where $|k_0 - k_{359}| \leq DOI$

DOI depicts the maximum variance of path loss in every direction. Equation (3.4) requires information about the angle between communicating nodes to determine path loss in all directions and one has to generate 360 values of k_i for 360 different directions. So, implementation of this is very complex. A simpler model is proposed by Xiao et.al [18] which does not need information about angle between two sensor nodes. So, DOI-adjusted path loss is represented as

$$PL(d)_{DOI} = PL(d) \times (1 \pm rand \times DOI) \tag{3.5}$$

The strength of received signal $P_r(d)$ at distance d applying DOI-adjusted path loss is

$$P_r(d) = P_s - PL(d)_{DOI} + P_f \tag{3.6}$$

Where, P_f is the fading exponent and P_s is the transmitted signal power. Hence, from equation (3.6), probability of signal received when its power level goes past a given threshold is

$$P_r\left(P_r(d) \geq \gamma\right) = \frac{1}{2} erfc\left(\frac{\gamma - \overline{P_r(d)}}{\sigma\sqrt{2}}\right) \tag{3.7}$$

In this equation γ is the threshold value of the received signal power. Using the equation (3.7), a sensor node can calculate it’s communicating range. Communication range is different for every node and it has dependency on the shadowing effects.

3.3 *k*- Sensing Coverage

Coverage refers to monitoring of object or area by sensors. If every single point in the target area is observed by at least one sensor then it is known as 1-coverage. To improve the accuracy and to overcome the effect of sensor failure, a few applications, such as intruder detection, military surveillance, and forest fire detection, require k-coverage (k > 1). For obstacle free environments the radius of sensing of a node is supposed to be fixed in all directions, but in real network the sensing radius is non-uniform in all directions due to the effects such as reflection, diffraction and scattering of signals. A node detects the sensing signal, if strength of the received signal is greater than a particular threshold. This is called as sensing sensitivity. For an average sensing radius of $\bar{r}$, the sensing sensitivity P_{senst} [19] of a node is given as

$$P_{senst} = P_s - \overline{L}\left(d_0\right) - 10\eta \log_{10}\left(\overline{r} / d_0\right) \tag{3.8}$$

Where, P_s is transmitting power, d_0 is reference distance and η is the path loss component.

3.3.1 *k*-Sensing Coverage without Shadowing Impact

Let A and $r_{\max}$ be the area of interest and effective sensing radius of a node, respectively when $\sigma = 0$. Target in the area A can be detected by any of the randomly deployed sensor, if it is in the range of sensing radius $r_{\max}$ from the event. So the probability, that a target is found by an arbitrary sensor

$$P = \pi r_{\max}^2 / A \tag{3.9}$$

The probability of a target not sensed by a sensor (randomly deployed) is

$$P_{\text{undet}} = \left(1 - P\right)$$

Let N sensors are deployed randomly in the region of interest. So the probability of the target not sensed by any of the sensor node is

$$P_{\text{undet}} = \left(1 - P\right)^N$$

$$P_{\text{undet}} = \left(1 - \pi r_{\max}^2 / A\right)^N$$

The probability that a target can be detected by at least one of N sensor node is

$$P_{\text{det}} = \left(1 - P_{\text{undet}}\right)$$

$$P_{\text{det}} = \left(1 - \left(1 - \pi r_{\max}^2 / A\right)^N\right) \tag{3.10}$$

The effective sensing range $r_{\max}$ of a given node [20] can be calculated as

$$r_{\max} = 10^{\psi} e^{\xi} \tag{3.11}$$

With $\psi = \lambda / 10 \times \eta, \xi = \left(\ln(10) \times \frac{\sigma}{10} \times \eta \right)^2$

3.3.2 *k*-Sensing Coverage with Impact of Shadowing

In a shadowing environment, sensing radius of a sensor node is anisotropic in all the directions. Let's assume that a node is being deployed at a distance x from the location of the target as shown in Fig. 3. 2; therefore, the received power (dB) can be expressed as

$$P_r(x) = P_s - P\overline{L}(d_0) - 10n \log\left(\frac{x}{d_0}\right) + X_{\sigma} \tag{3.12}$$

A target is sensed by the node when the power of received signal is larger than some predefined threshold value γ. Probability that the power of received signal is larger than some threshold value can be given as

$$P_{sens}\left[P_r(x) > \gamma\right] = Q\left(\frac{\gamma - \overline{P_r(x)}}{\sigma}\right) \tag{3.13}$$

Here, Q function is used to compute the probability that the power of received signal exceeds threshold value and is given as

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_{z}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx \tag{3.14}$$

Sensor nodes are randomly deployed in an area A. The probability that a node is at a distance x from the event of interest is $2\pi x dx / A$. Here dx is a very small change in distance. Probability that the event of concern is sensed by the node is

$$P_{\det} = \int_{0}^{r_{\max}} P_{sens} \times \frac{2\pi x}{A} dx \tag{3.15}$$

Probability that the target is sensed by M sensors out of N sensors in sensing field with area A is

$$P_{K\ \mathrm{cov}}(M) = \binom{N}{M} (P_{\det})^{M} (1 - P_{\det})^{N-M} \tag{3.16}$$

Substituting the value of $P_{\det}$ from equation (3.15)

$$P_{K\ \mathrm{cov}}(M) = \binom{N}{M} \left(\int_{0}^{r_{\max}} Q\left(\frac{\gamma - \overline{P_r(x)}}{\sigma} \right) \times \frac{2\pi x}{A} dx \right)^{M} \left(1 - \left(\int_{0}^{r_{\max}} Q\left(\frac{\gamma - \overline{P_r(x)}}{\sigma} \right) \times \frac{2\pi x}{A} dx \right) \right)^{N-M} \tag{3.17}$$

Probability that K sensors can cover up the target location is given by

$$P_{K\ \mathrm{cov}}(K) = 1 - \sum_{M=0}^{K-1} \binom{N}{M} \left(\int_{0}^{r_{\max}} Q\left(\frac{\gamma - \overline{P_r(x)}}{\sigma} \right) \times \frac{2\pi x}{A} dx \right)^{M} \left(1 - \left(\int_{0}^{r_{\max}} Q\left(\frac{\gamma - \overline{P_r(x)}}{\sigma} \right) \times \frac{2\pi x}{A} dx \right) \right)^{N-M} \tag{3.18}$$

From this equation (3.18), we can find the probability of k-coverage to make the network fault tolerable. It can also be observed that when shadowing parameter increases, the coverage probability decreases.

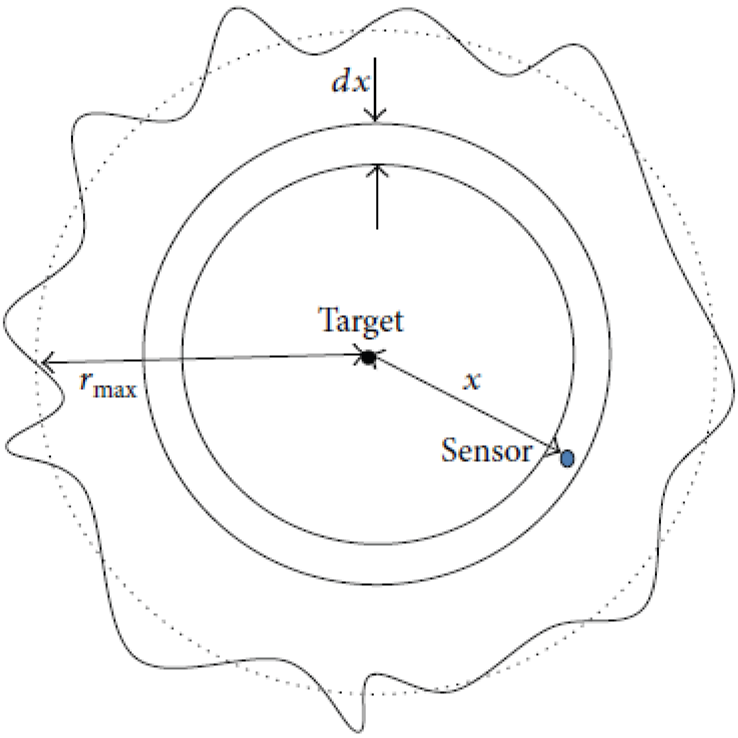


Fig. 3.2 Impact of Shadowing Environment on Sensing

3.4 q-Connectivity

In Wireless Sensor Networks, a sensor node sends its observed data to the sink using multi-hop communication. Therefore, to provide successful multi-hop communication, connectivity may be ensured in the network. Connectivity in a sensor network is affected by node failure due to energy depletion of nodes. q-connectivity is an important QoS parameter of network for providing fault tolerant to enhance the reliability of communication. q-connectivity refers to the basic property of a randomly selected sensor node which has at least q neighbours i.e. if $(q-1)$ node fails, connectivity still holds. A wireless channel is affected by various environment impairments. q-connectivity performance is evaluated using log-normal model of shadowing.

3.4.1 Geometric Random Graph Model.

Any random graph can be denoted by $Gp(N)$, where p is the probability of holding link between any two nodes and N is the number of nodes. The node degree in a network is stated as the number of links or connections the node has with other nodes. In a random graph, each pair of nodes is connected is given by probability p and not connected is given by probability $(1-p)$. Therefore, the probability that a node has degrees q can be expressed using binomial distribution.

$$P(q)=\binom{N-1}{q}P^q(1-p)^{N-1-q} \tag{3.19}$$

For a small value of q and large value of N and we are using the following approximations

$$\binom{N-1}{q}=\frac{(N-1)!}{q!(N-1-q)!}$$

$$\frac{(N-1)!}{q!(N-1-q)!}=\frac{(N-1)(N-1-1)(N-1-2)....(N-1-q)!}{q!(N-1-q)!}$$

Therefore,

$$\binom{N-1}{q}=\frac{(N-1)^q}{q!}$$

The Poisson approximation for large value of Nis given by

$$P(q)=\binom{N-1}{q}P^q(1-p)^{N-1-q}=\frac{(N-1)^q}{q!}P^qe^{-m}=e^{-m}\frac{m^q}{q!} \tag{3.20}$$

Where m is the mean degree of a node $m=p(N-1)$.

3.4.2 q-connectivity in presence of Shadowing

Let us assume a WSN where N sensor nodes are randomly distributed in accordance to a homogeneous Poisson process with intensity (average) λ in the area A. Here $\lambda = N/A$ depicts number of nodes per unit area. The probability of a randomly picked sensor node with area A has q neighbours is given by the following equation

$$P(q) = \frac{(\lambda A)^q}{q!} e^{-\lambda A} \qquad \text{Where, } (q = 1, 2, 3.....)$$

$$P(q) = \frac{\left(\lambda \pi r_{\max}^2\right)^q}{q!} e^{-\lambda \pi r_{\max}^2} \tag{3.21}$$

Probability of a randomly picked sensor node which has no neighbour i.e. the network is not connected is

$$P(q = 0) = e^{-\lambda \pi r_{\max}^2} \tag{3.22}$$

When a sensor node is isolated from all other sensors, it cannot switch information between other nodes and therefore, it is not useful for the whole network. There is a relationship between the minimum node degree and q-connectivity [21] i.e. $p(q - connectivity) \approx p(d_{\min} \geq q)$. So we can directly apply the expression for minimum node degree to q-Connectivity. The received signal range is not symmetrical in all directions due to the effect of shadowing. So the receivers which are locating at the same distance from the transmitter may have different received signal strength. The probability that each sensor node with effective transmission range $r_{\max}$ is q-cconnected is given by the following expression

$$p(d_{\min} \geq q) = \left(1 - e^{-\lambda \pi r_{\max}^2} \left(1 + \lambda \pi r_{\max}^2 + \frac{\left(\lambda \pi r_{\max}^2\right)^2}{2} + ... + \frac{\left(\lambda \pi r_{\max}^2\right)^{q-1}}{q - 1!}\right)\right) \tag{3.23}$$

Chapter 4

Results and Performance Analysis

In this chapter, we are doing the performance analysis of a network for k-Coverage and q-Connectivity. Here all nodes are using the lognormal shadowing model for sensing and communication. All the Simulations are performed utilizing MATLAB to find the k-Coverage and q-Connectivity results. Simulation parameters (values) used in the simulation is given in Table 4.1, 4.2, 4.3. To find out the effect of node density and shadowing, we have conducted the following simulations:

- Effect of standard deviation and node density on sensing coverage
- Effect of node density on connectivity
- Effect of communication range on connectivity

4.1 Effect of Standard Deviation and Node Density on Sensing Coverage

Parameter	**value**
Number of sensor nodes (N)	100
Area (A)	1000 m^2 to 3000 m^2
Path loss exponent(η)	3
Transmission power of a sensor node (P_s)	20W
Threshold of received signal (γ)	-58 dB
Effective sensing range ($r_{\max}$)	10m

Table 4.1 Simulation parameters for Coverage

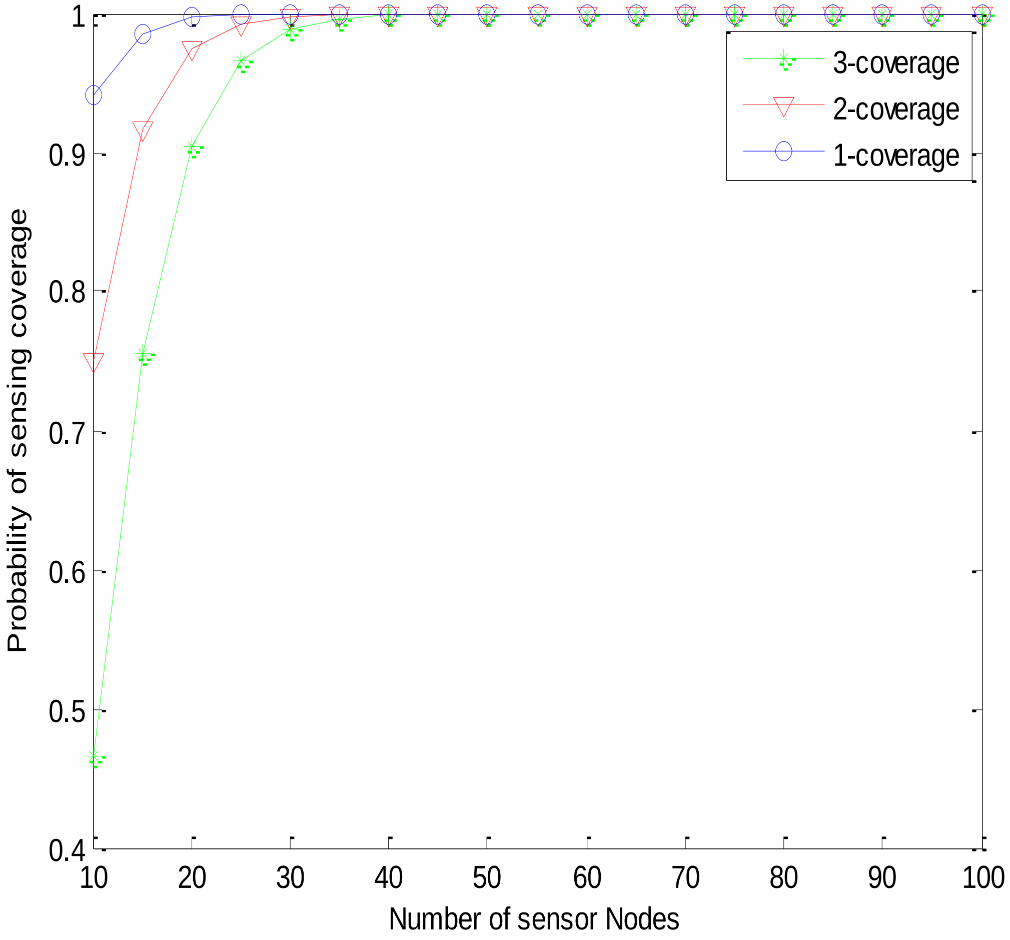


Fig. 4.1 Coverage probability versus sensor nodes at standard deviation $\sigma = 2$ (A=1000 m^2)

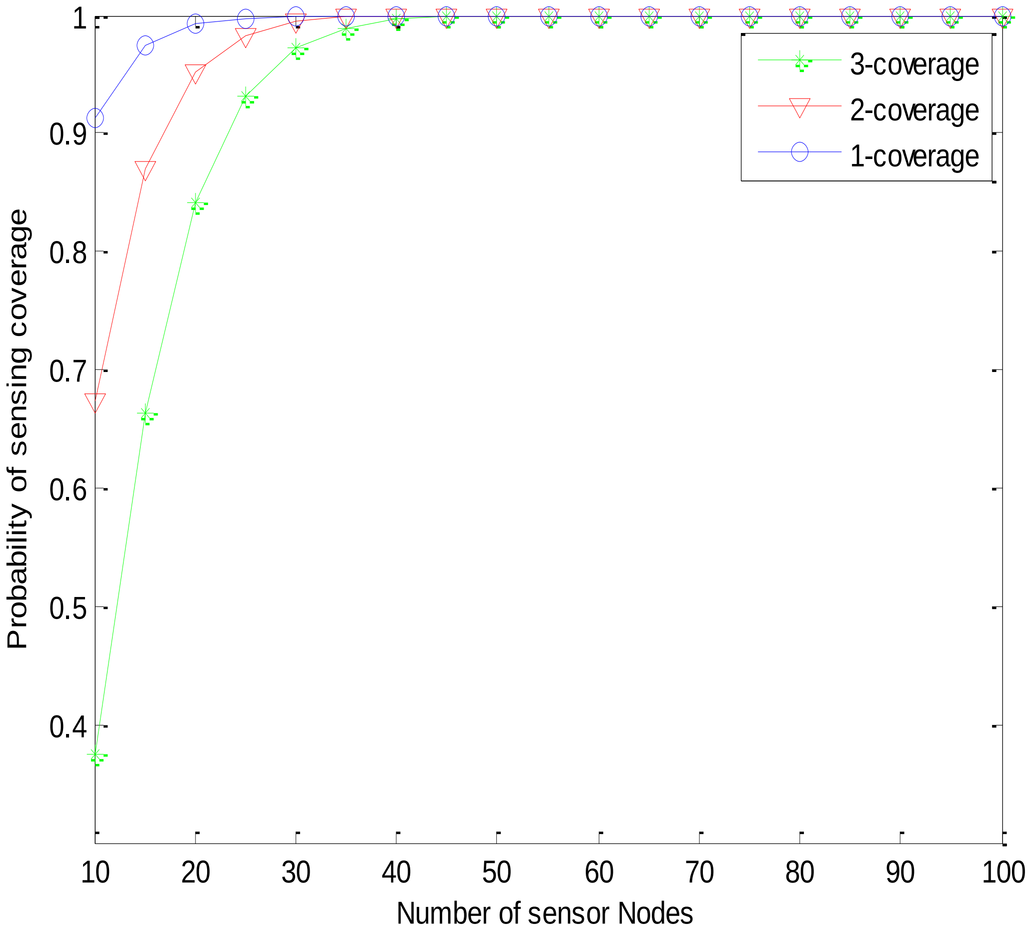


Fig. 4.2 Coverage probability versus sensor nodes at standard deviation $\sigma = 4$ **(A=1000 m^2)**

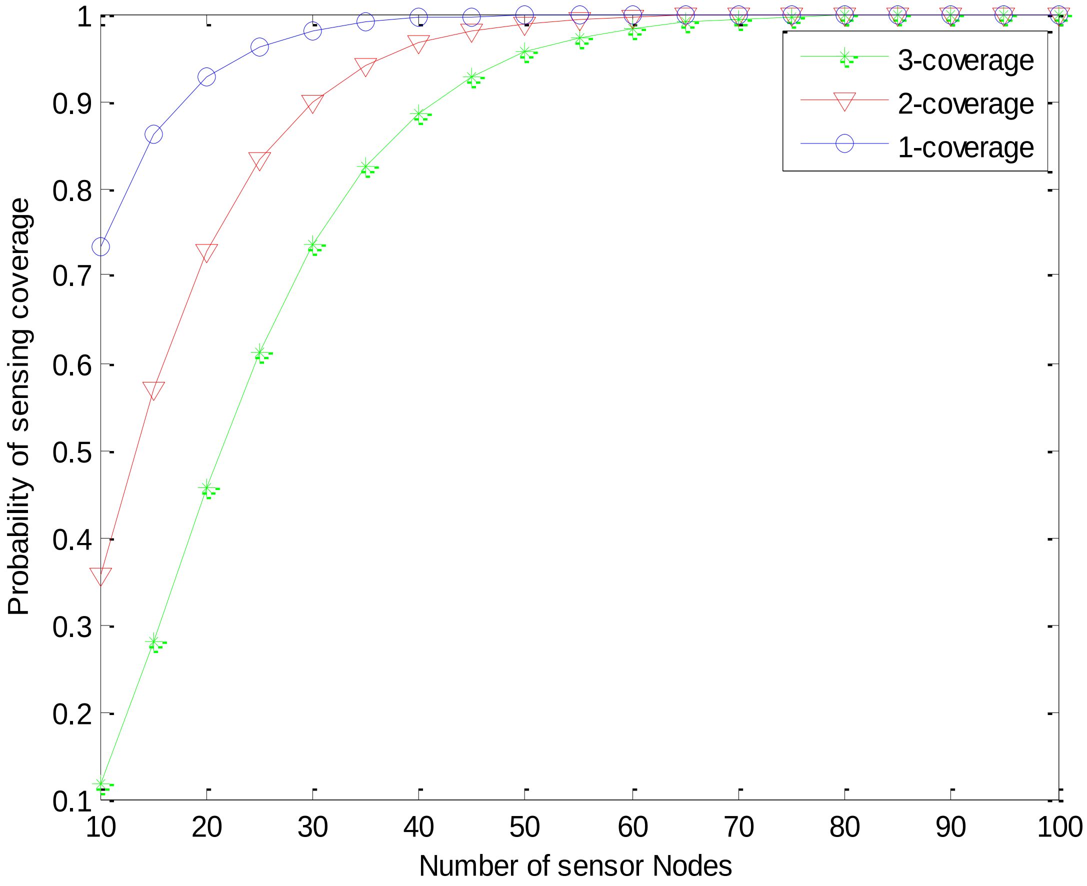


Fig. 4.3 Coverage probability versus sensor nodes at standard deviation σ = 2 (A=2000 m^2)

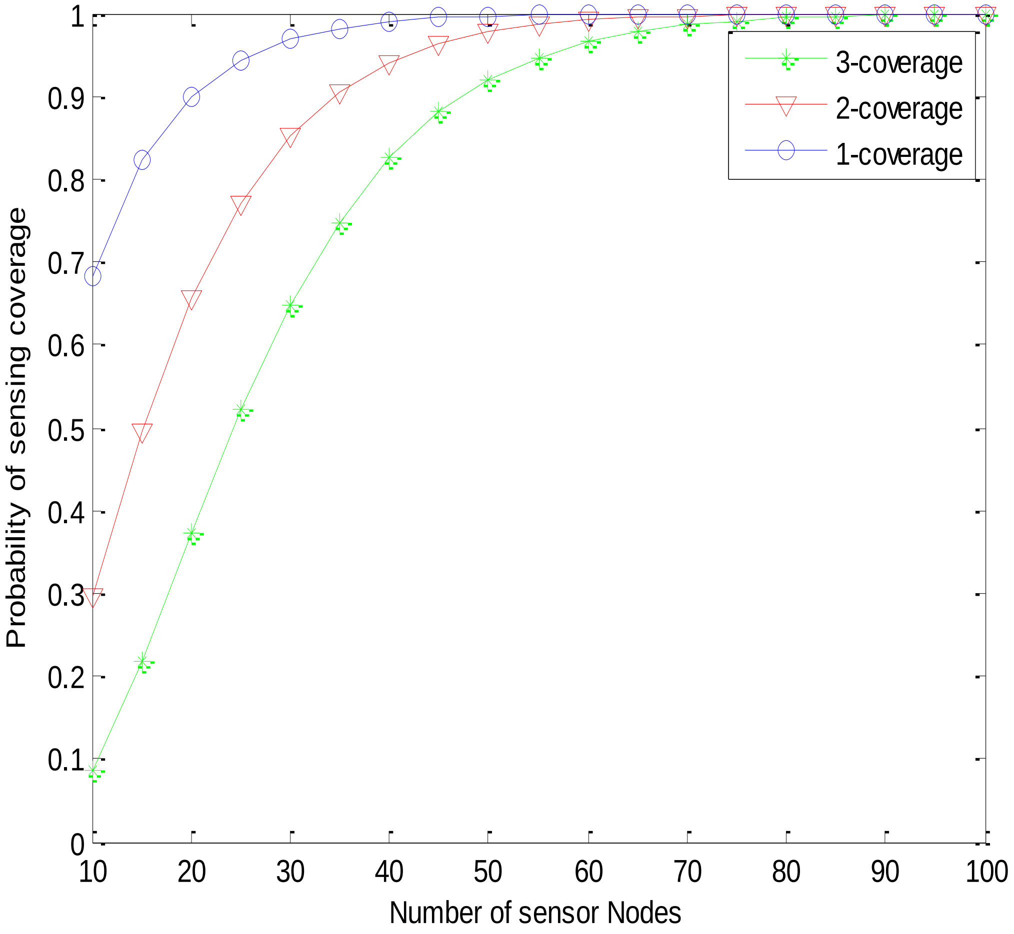


Fig. 4.4 Coverage probability versus sensor nodes at standard deviation $\sigma = 4$ (A=2000 m^2)

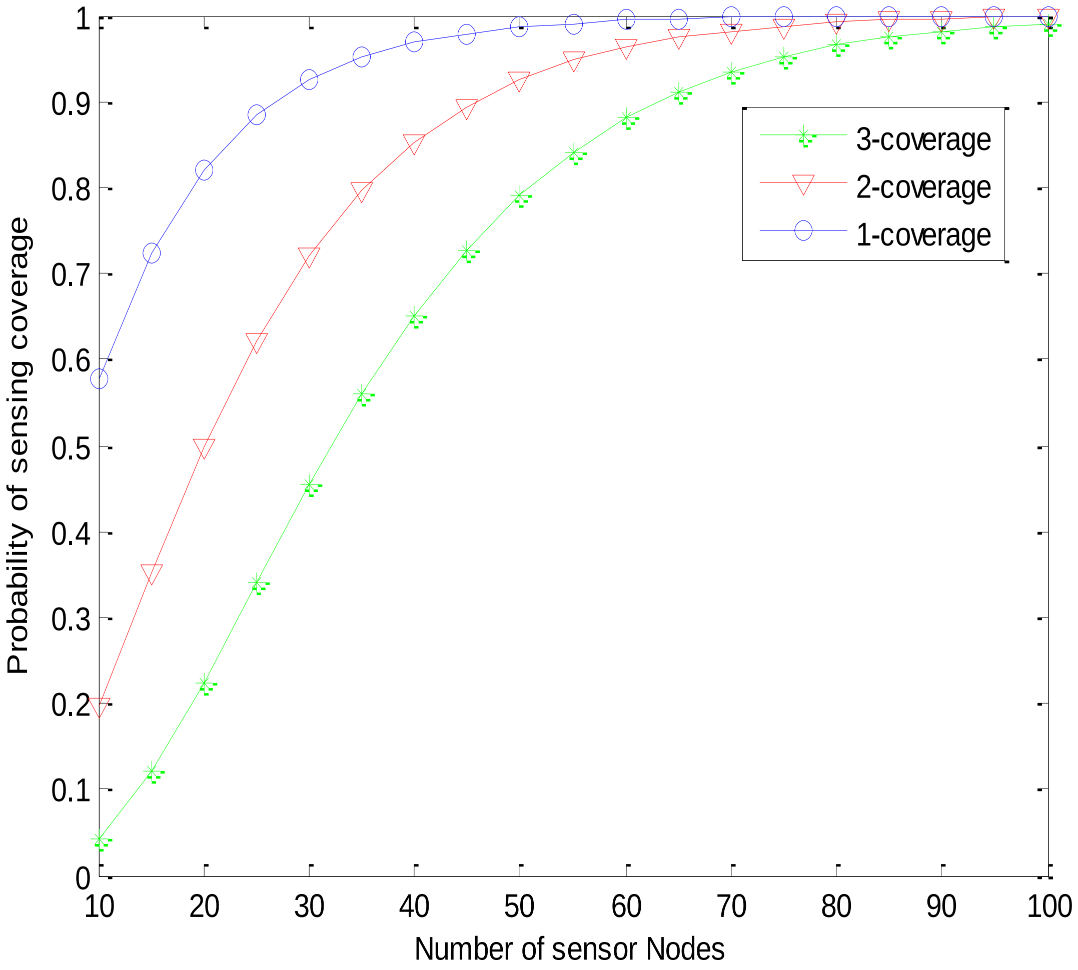


Fig. 4.5 Coverage probability versus sensor nodes at standard deviation $\sigma = 2$ (A=3000 m^2)

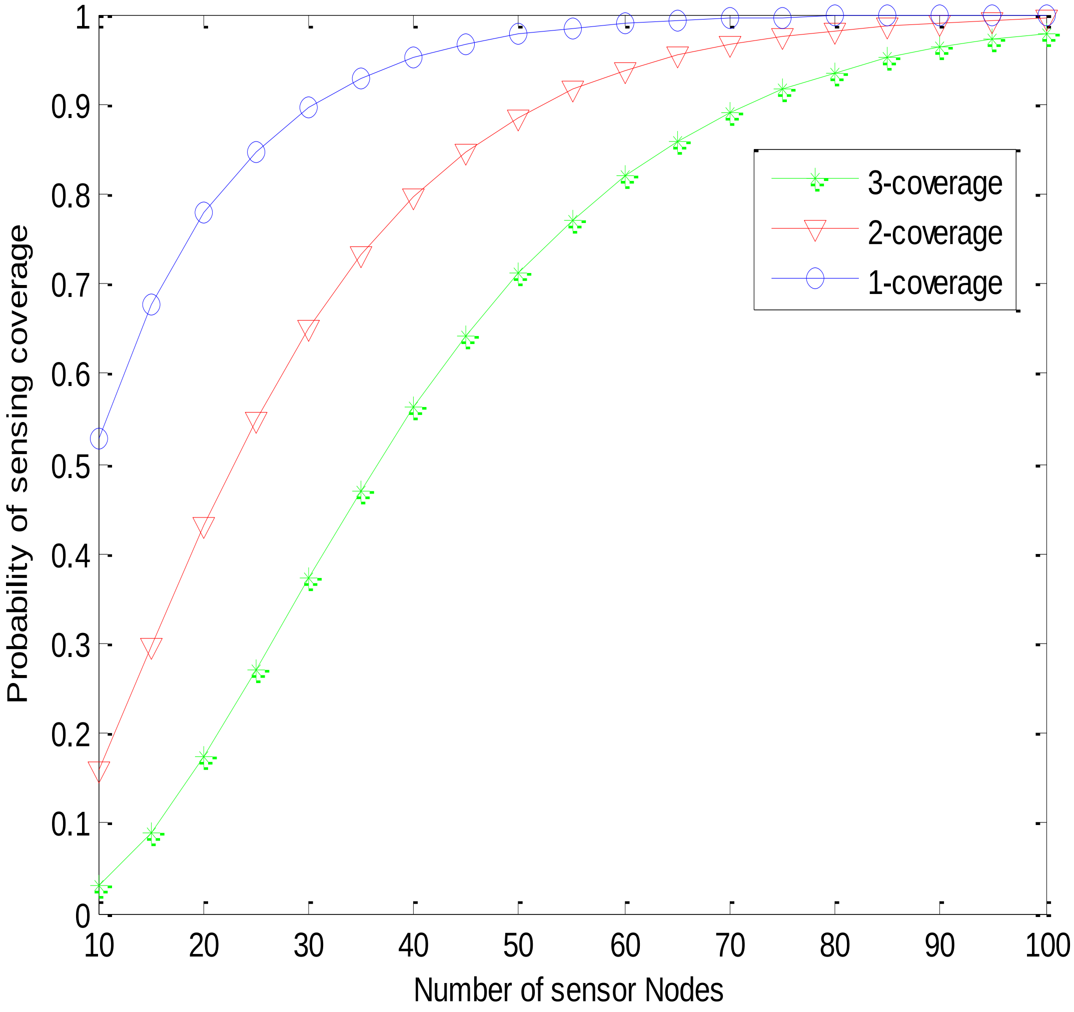


Fig. 4.6: Coverage probability versus sensor nodes at standard deviation $\sigma = 4$ ($A=3000\ m^2$)

We have drawn Figure (4.1), (4.2), (4.3), (4.4), (4.5), (4.6), for different shadowing parameters (σ = 2, 4) and Area values (A=1000, 2000, 3000 m^2). When standard deviation is changed from 2 to 4, probability of coverage decreases. So, we require more sensor nodes to achieve the same coverage for σ = 4 as compared to σ = 2. Also we can see the effect of increasing Area on probability of coverage for constant number of sensor nodes. When area is increasing Probability of coverage is also decreasing.

4.2 Effect of Node Density on Connectivity

Parameter	value
Number of sensor nodes (N)	100
Area (A)	1000 m^2 to 4000 m^2
Effective sensing range ($r_{\max}$)	10m

Table 4.2 Simulation parameters for Connectivity

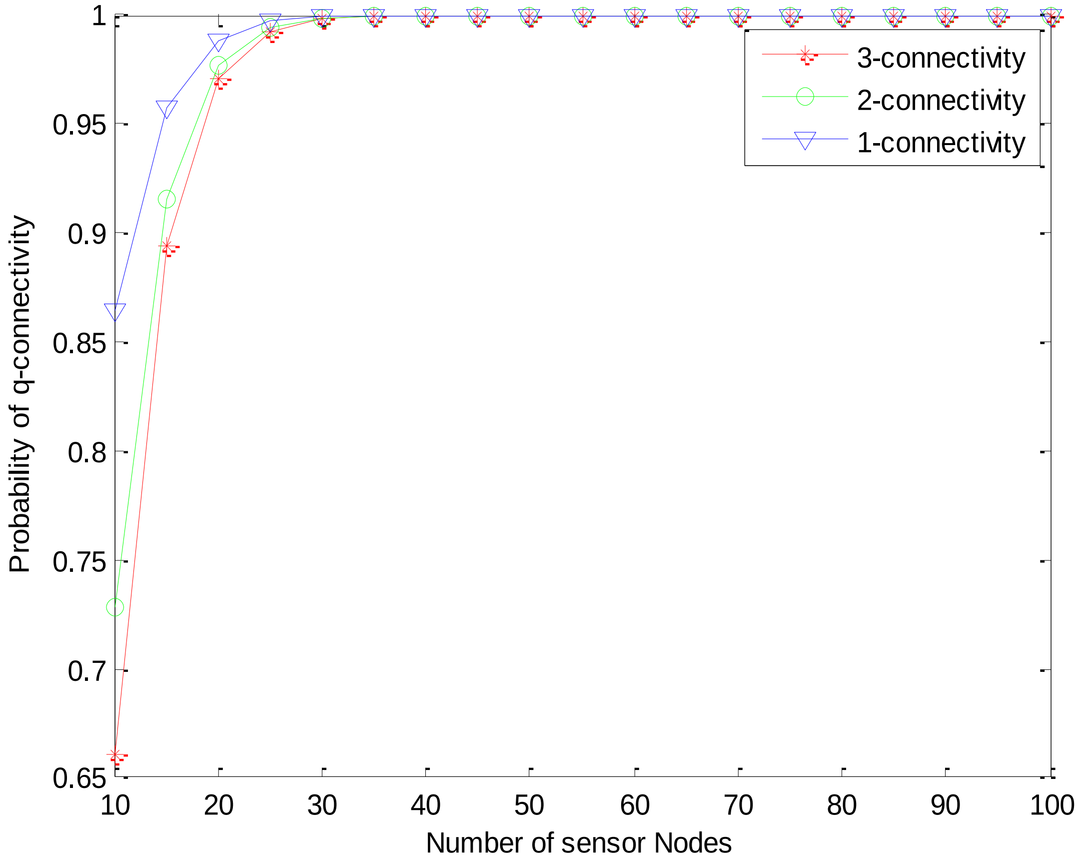


Fig. 4.7: Probabaility of K-connectivity versus number of sensor nodes (A=1000 m^2)

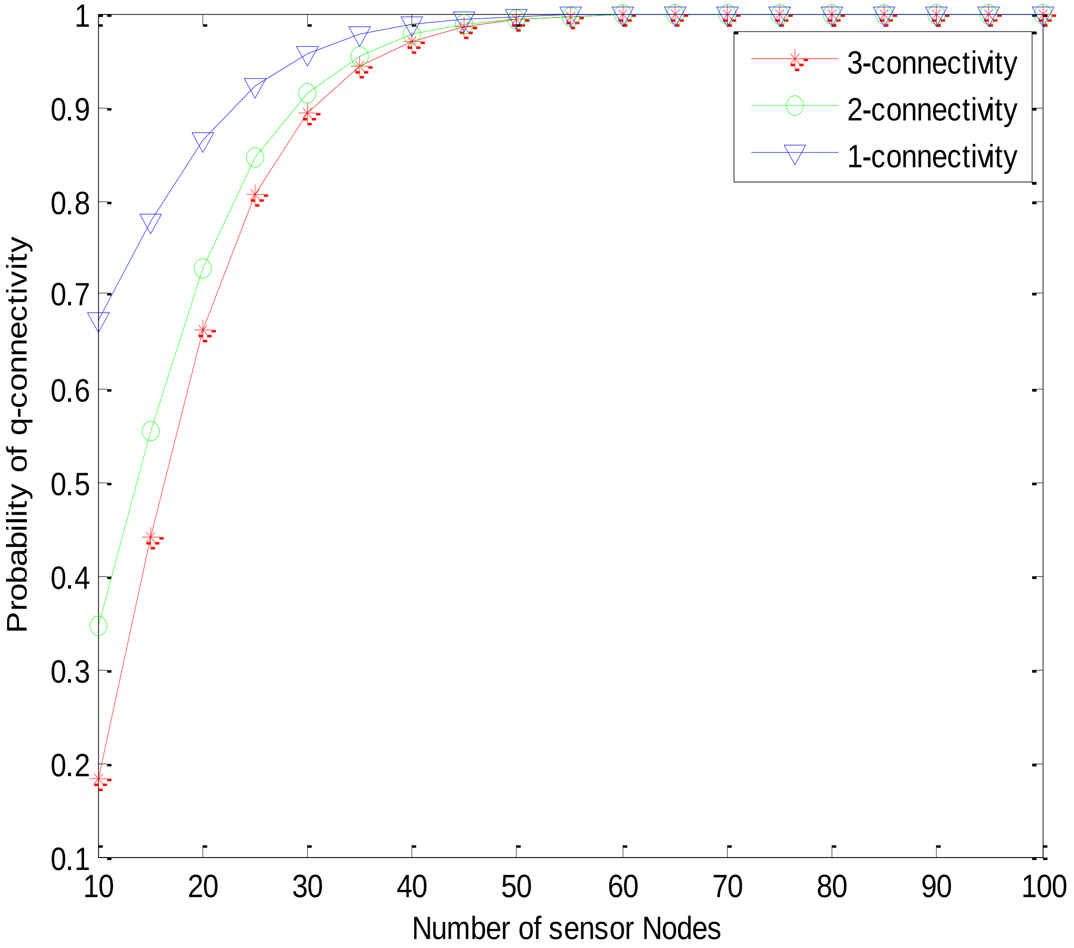


Fig. 4.8: Probabaility of K-connectivity versus number of sensor nodes (A=2000 m^2)

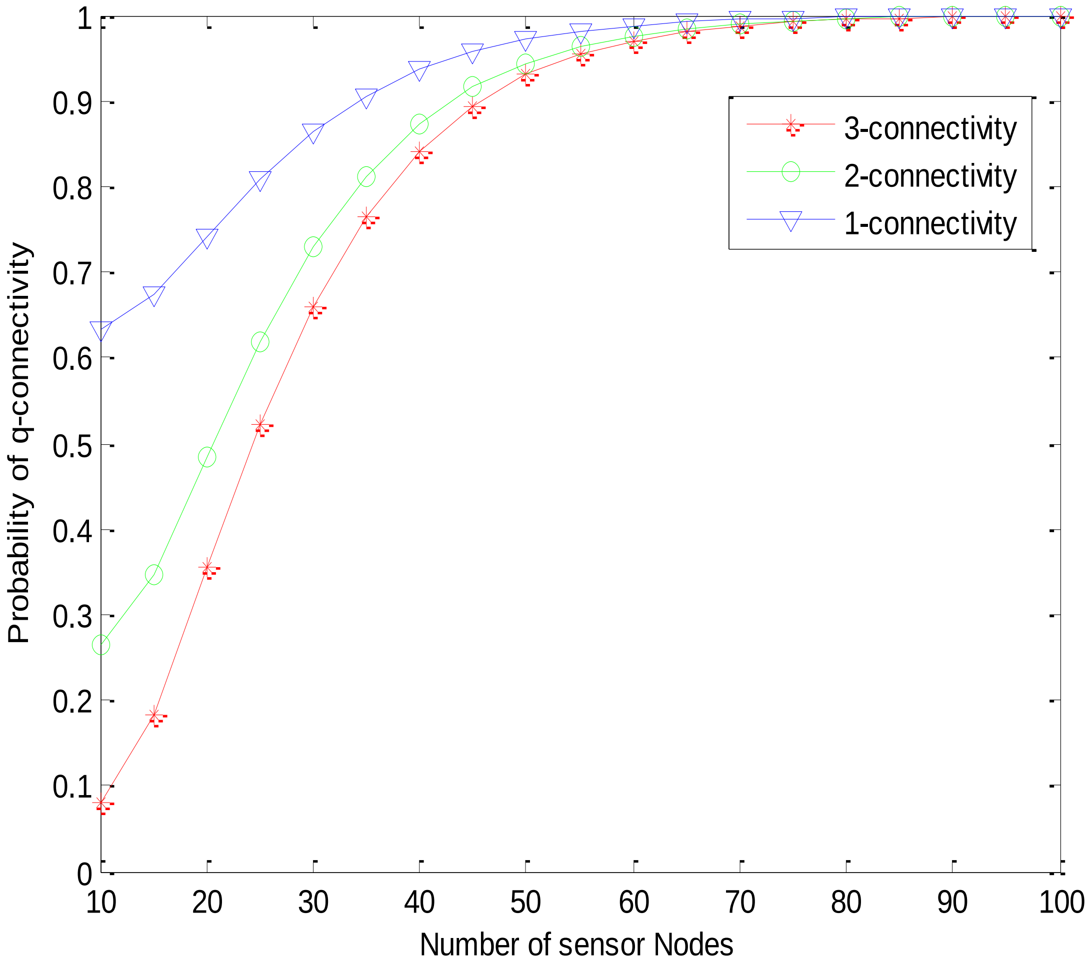


Fig. 4.9: Probabaility of K-connectivity versus number of sensor nodes (A=3000 m^2)

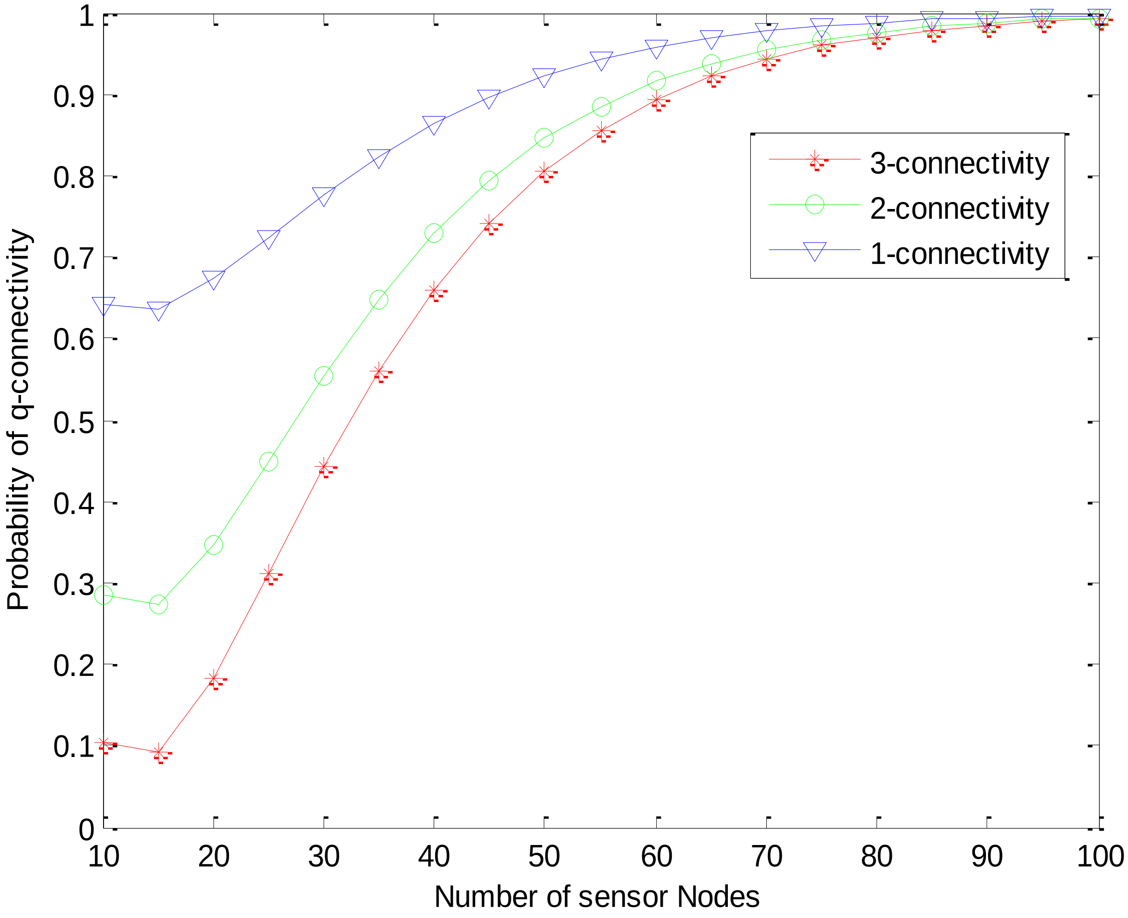


Fig. 4.10: Probabaility of K-connectivity versus number of sensor nodes(A=4000 m^2)

Figure (4.7), (4.8), (4.9), (4.10) show the variation between probability of *k*-connectivity with number of sensor nodes (*N*). As the number of sensor node increases, the graph shows changeover from low value of connectivity to high value of connectivity. From these graphs we can conclude that for network connectivity greater than or equal to 90%, we require at least 15 sensors (Area A=1000 m$^{2)}$. Similarly for A=2000 m^2 at least 30 sensors, for A=3000 m^2 at least 45 sensors, for A=4000 m^2 at least 60 sensors, are required. It shows the effect of Area on the connectivity. If the area of interest increases, simultaneously the need of sensors for a surely connected network (connectivity greater than or equal to 90%) also increases.

4.3 Effect of Communication Range on Connectivity

Parameter	**Value**
Number of sensor nodes (N)	100,150,200
Area (A)	1000 m^2
Effective sensing range ($r_{\max}$)	5 m to 25 m

Table 4.3 Simulation parameters for Communication range

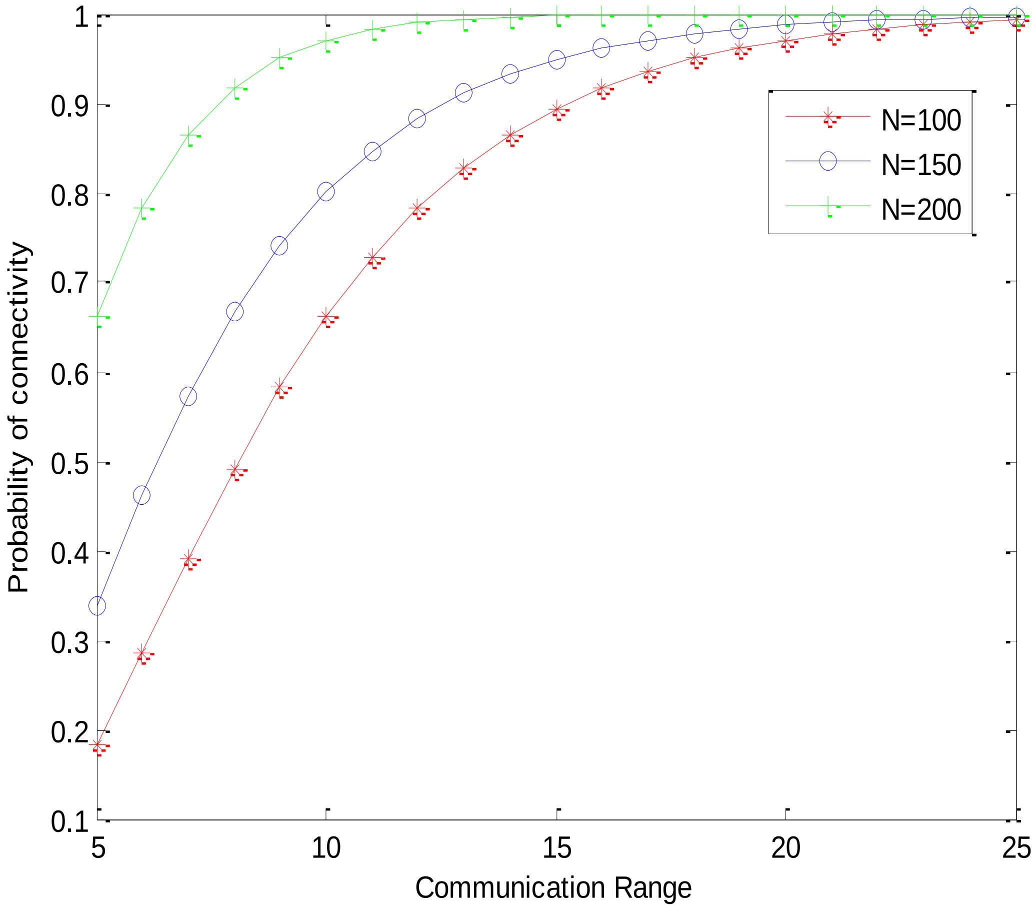


Figure 4.11: Probability of Connectivity versus communication range (A=1000m^2)

In figure (4.11) we have plotted probability of connectivity vs. communication range. From this we can find that network connectivity is affected by communication range. When the communication range increases, the connectivity of the network also increases. For *N=100* to get the connectivity greater than 90% approx 16 meter communication range is required. Whereas for *N=150* communication range required is approx 13 meter and for *N=200* communication range required is approx 8 meter. So high connectivity can be achieved by increasing the communication range for less number of nodes.

Chapter 5

Conclusion and Future Scope

5.1 Conclusions

Fault tolerance is one of the most important QoS parameter in the designing of WSN. In this chapter we have evaluated k-coverage and q-connectivity under lognormal shadowing model. We have shown the effect of node density and shadowing parameter on coverage. We observed that the probability of network connectivity and coverage depends on the standard deviation and node density. For a high value of standard deviation, the probability of network coverage decreases. So we can conclude that there is a significant impact of node density and path loss model (log-normal) on coverage and connectivity.

The contribution to this thesis are a set of studies various mathematical models and analysis of these mathematical models through simulation. The main contribution of this thesis are summerized below-

- We have developed k-coverage and q-connectivity model model to make the network fault tolerable and reliable.
- Log normal shadowing path loss to capture the radio irregularities has been used to to make the k-coverage and q-connectivity model more realistic.

The model developed in this thesis has been evaluated analytical as well as through simulations. After examining the simulation results the following observations have been are made on finding of this work

- More number of sensors is required to maintain the threshold level of coverage when standard deviation of the shadowing environment increases.
- Coverage and connectivity increases when the density of sensor node increases.
- When the communication range increases the connectivity of the network also increases.

5.2 Future Scope

There are various possibilities of for further investigation of the research work presented in this thesis. Some of these possibilities are given below as future direction of research

- This work can also be extended for mobile wireless sensor network so that target tracking can be performed continuously.
- The model developed in this work can be extended for 3-D wireless sensor network such as under water sensor network.
- Substantially more precise propagation models indicating the variation in the radio range with respect to time may be designed.

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