CHAPTER 3

OPTIMAL DESIGN OF WIRELESS SENSOR NETWORK FOR IONIZING RADIATION DETECTION

3.1 INTRODUCTION

A nuclear power plant is an important alternative energy source and is one of the most important applications of nuclear technology. Nuclear reactors operate within rooms with multiple concrete barriers, and the rooms have a reduced pressure so that any leaks occur into the room and not out of it. Nuclear power plants produce large quantities of ionizing radiation as a by-product of fission during their operation. In addition, they also produce highly radioactive nuclear waste, which will emit ionizing radiation for many years.

A real time monitoring and control system for monitoring the possible presence of ionizing radiation in the region around a nuclear power plant is needed for ensuring safety. Safety must be considered as the most important issue in a nuclear power plant, since leakage of ionizing radiations presents a health hazard and exposure to radiation results in mutation, radiation sickness, cancer etc. Ionizing radiations are invisible and not detectable by human senses directly.

This chapter deals with the optimal design of a WSN with parallel architecture, using Neyman Pearson methodology for the detection of ionizing radiation. The remainder of this chapter is organized as follows: the
challenges faced in the design problem are listed in Section 3.2. The design of the WSN for radiation detection is presented in Section 3.3 and the problem formulation is given in Section 3.4. Performance measures used in assessing the performance are defined in Section 3.5. The trade-off between the design parameters for the individual node is described in Section 3.6, and the threshold design equations are derived for the network in Section 3.7. The detection performance of an individual node, and a network of sensor nodes under two different operating options, are presented in Section 3.8 for different network parameters and sensor characteristics, to understand the constraints, and design trade-offs that apply to real world deployment of sensor node with radiation detection instruments. The concluding remarks are given in Section 3.9.

3.2 CHALLENGES

The problem of designing WSN for nuclear radiation detection application is challenging due to the following difficulties:

- Ionizing radiations are ubiquitous in the environment and the natural background radiation rate varies with the location.
- Early detection of radiation leaks, to mitigate a nuclear disaster is a challenging task.
- Radiation sensors are expensive, high precision devices which require more power, and the deployment of a large number of sensors is infeasible.
- An appropriate network topology is to be selected. And, it is very important to understand the design trade offs between sensor network parameters and performance measures.
3.3 DESIGN OF WIRELESS SENSOR NETWORK FOR RADIATION DETECTION

A WSN can be deployed for monitoring the possible presence of ionizing radiation in the region around a nuclear power plant. A Geiger counter that can detect alpha, beta and gamma rays can be used as the sensor in the sensor node. The Geiger counter is one of many different types of radiation detectors, and are widely used since they are cheap and robust. The GM (Geiger Muller) counter can detect the presence and intensity of ionizing radiation. Commercially available GM counters have graduations in Roentgens, which is a unit of measurement of the exposure to ionizing radiation.

3.3.1 Operational Requirements

A variety of operational requirements governs the deployment of a network of radiation sensors for detecting ionizing radiations. Some of the operational requirements are:

- Geographical extent: To ensure that the detecting system has the ability to detect ionizing radiations across a geographical region, it is required to deploy radiation sensors at a number of different locations.

- Additional Information: A network of sensors can provide information about the source’s position, direction and nature within an extended region, apart from accomplishing the task of detection.

- Signal-to-noise ratio: A system comprising a network of radiation sensors operates collaboratively to detect the presence of ionizing radiations. Good improvement in the
signal-to-noise ratio is obtained by a simple combination of
data from networked sensors, compared to a single sensor.

- Reliability: The tolerance of the detecting system for faults or
  node failure is improved by the deployment of multiple
  sensors emplaced at different locations.

3.3.2 Operating Options

The design of a WSN for radiation detection is formulated as a
binary hypothesis testing problem with the \( H_0 \) hypothesis indicating the
absence of any radiation source and the \( H_1 \) hypothesis indicating the presence
of the radiation source. The \( i \)th sensor \( S_i \) makes observation \( X_i \) and the
observations made by the sensors under both hypotheses are

\[
H_0 : X_i = b_i + m_i \\
H_1 : X_i = c_i + b_i + m_i
\]  \hspace{1cm} i = 1, 2, 3, 4, \ldots, \text{N} \tag{3.1}

where \( c_i, b_i \) and \( m_i \) are the source radiation count, background radiation count
and the count due to measurement noise respectively.

In the system employing a centralized detection scheme, each
sensor node passes the observed information to the fusion centre. The fusion
centre arrives at a global decision based on the received unprocessed
information and global decision rule.

In the system employing a decentralized detection scheme, each
sensor node records the radiation counts based on the intensity of radiation,
and a decision is made based on a local threshold. The binary decisions made
at the individual sensors are transmitted to a fusion centre, which combines
them to make a final decision on the presence or absence of the radiation. The
design problem thus consists of determining the individual sensor thresholds to form sensor decisions, and a global decision threshold for global inference.

3.4 NEYMAN PEARSON FORMULATION OF THE DETECTION PROBLEM

Under the Neyman Pearson formulation, in a decentralized detection scheme, for the given prescribed bound on the global probability of a false alarm, the local and global decision rules \((\Gamma_{ed}, \Gamma_{ld}, \Gamma_{2d}, \ldots, \Gamma_{Nd})\) are determined such that the global probability of miss detection is the minimum. This detection methodology is also applicable to centralized detection, where the global decision rule is determined such that the global probability of miss detection is the minimum, for the prescribed global false alarm probability. Variations of this formulation include the optimization of only the fusion rule for a given set of local decision rules, and the optimization of only the local decision rules for a given fusion rule. A detailed account on Neyman Pearson criteria is given in Appendix 1.

The Neyman Pearson formulation is suitable for detection applications, where it is difficult to assign realistic costs or \textit{a priori} probabilities for the event. For radiation detection, the WSN is designed using the Neyman-Pearson criterion, since it is difficult to assign realistic costs or \textit{a priori} probabilities to the radiation phenomena.

For the problem under consideration, the WSN is designed as a homogeneous network, since the location of the source is deterministic. All the nodes are deployed in such a way that they are equidistant from the source, and this ensures identical hit rates and false alarm rates.

Background radiation is assumed to be uniform at all points in the region of interest, and the measurement noise is considered to be negligible.
Assuming an ideal channel between the sensors and the fusion centre, the network is designed with parallel architecture as shown in Figure 3.1, focusing only on the signal-processing task. For the prescribed global false alarm probability, the sensor thresholds, and that for the fusion centre are determined such that the global probability of miss detection is the minimum. This constrained nonlinear optimization problem is solved, using a well known optimization algorithm.

![Figure 3.1 Parallel topology with the fusion centre](image)

3.5 PERFORMANCE MEASURES FOR THE RADIATION DETECTOR

The main objective of this work is to compare the tradeoffs of various design parameters when designing a WSN for radiation detection. For evaluating the detection performance the following metrics are used.
i) Time to detect

ii) Receiver Operating Characteristics

iii) Robustness

3.5.1 Time to Detect

Radiation detection systems are expected to detect ionizing radiations rapidly with a high detection efficiency and a low false alarm rate. This ensures confident and timely detection of radiation, while minimizing the resources consumed for false alarms. The time to detect (T) is the time taken by the sensor to make a decision. This is a function of the photon generation rate by the source, spacing between the source and the detector, photon absorption rate per meter in air, size of the detector crystal, background radiation rate, and the rate of photons detected by the sensor when the source is present.

3.5.2 Receiver Operating Characteristics

The Receiver Operating Characteristics (ROC) curve is a plot of detection probability as a function of the probability of false alarm for different possible discriminating thresholds.

The parameter detection probability is the probability that the sensor network will detect nuclear radiation when the radiation is actually present. The probability of false alarm is defined as the probability that the sensor network will incorrectly identify the presence of radiation when it is not actually present. ROC curves provide the design engineer with an insight to select the optimal design parameters, and give an idea about the detection accuracy of the system.
3.5.3 Robustness

The robustness of the network in detection performance against node failure is another key issue, for the WSN designed for radiation detection. The robustness of the wireless sensor network to node failure is analyzed using the plot, which is the function of the detection error probability and the number of nodes.

3.6 TRADE OFF BETWEEN DESIGN PARAMETERS FOR THE INDIVIDUAL SENSOR NODE

Ionizing radiations are showers of individual photons, and hence, the number of photons could be used to express the amount of radiation in principle. The radiation source generates photons in a Poisson manner. In this analysis, the radiation source is approximated as a point source since the detectors are far from the source. It is also assumed that photons are sent with equal intensity in all directions.

The background radiation from the material and cosmic rays is assumed to be uniform at all points in the area. These background radiations do not vary much in the small area, and are modeled with a fixed probability of photon hits at the detector.

Assuming that there is no scattering of photons and $\mu$ represents the photon generation rate by the source; $r$ represents the spacing between the source and the detector; $\alpha$ represents the photon absorption rate per meter in air; $A$ represents the proportionality constant, which depends on the area of the detection crystal; $\lambda_1$ represents the rate of photons detected by the sensor when the source is not present (background radiation rate) and $\lambda_2$ represents the rate of photons detected by the sensor when the source is present.
\[ \lambda_2 = \frac{A \mu e^{-\kappa}}{\kappa^2} \]  \hspace{1cm} (3.2)

The probability of \( n_e \) events in time \( T \), when the events are generated in a Poisson manner at rate \( \lambda_e \) is given by

\[
\text{poisson}(\lambda_e, T, n_e) = \frac{(\lambda_e T)^n e^{-(\lambda_e T)}}{n_e!} \]  \hspace{1cm} (3.3)

Given that there is no source present, the probability of a false positive (Type I error) is computed as the probability of detecting \( \tau \) or more photons from the background rate of \( \lambda_1 \) in time \( T \).

The probability of type I error = \( \sum_{n_e > \tau} \text{poisson}(\lambda_1, T, n_e) \)  \hspace{1cm} (3.4)

When a source is present, the probability of a true positive is (complement of Type II error) given as the probability of detecting \( \tau \) or more photons in time \( T \).

The probability of detection = \( \sum_{n_e > \tau} \text{poisson}(\lambda_1 + \lambda_2, T, n_e) \)  \hspace{1cm} (3.5)

For a fixed bound on the probability of false alarm and probability of detection, the following equation is satisfied at a real positive value \( x \) on the boundary line in ROC space.

\[
\frac{(\lambda_1 + \lambda_2)T - \tau}{\sigma_{\text{source}}} = \frac{\tau - \lambda_1 T}{\sigma_{\text{null}}} = x
\]  \hspace{1cm} (3.6)

\[
x = \frac{\lambda_2 T}{\sqrt{\lambda_1 T} + \sqrt{(\lambda_1 + \lambda_2)T}}
\]  \hspace{1cm} (3.7)
where, $\sigma_{null} = \sqrt{\lambda_1 T}$ is the standard deviation of the number of photons detected by a sensor in time $T$ when no source is present, and $\sigma_{source} = \sqrt{(\lambda_1 + \lambda_2)T}$ is the standard deviation of the number of photons detected by a sensor when a source is present.

The time taken by the sensor ($T$) to make decisions is derived from the equation (3.7) as,

$$T = \frac{x^2 \left( \sqrt{\lambda_1} + \sqrt{\lambda_1 - \lambda_2} \right)^2}{\lambda_2} \quad (3.8)$$

If the photon absorption by the materials in the path between the source and the detector is ignored, $T$ is derived as,

$$T = \frac{x^2 \left[ \sqrt{\lambda_1} + \sqrt{\lambda_1 + \frac{A \mu}{r^2}} \right]^2}{\frac{A \mu}{r^2}} \quad (3.9)$$

### 3.7 THRESHOLD DESIGN EQUATIONS

#### 3.7.1 Threshold Design Equation for Centralized Detection

In a centralized detection scheme, the fusion centre adds the radiation counts from other sensors, and compares the sum to a threshold $\gamma_c$ to detect the presence of ionizing radiation.

The processes by which the photons are detected at each sensor are independent Poisson processes, and hence the total across all sensors is also a Poisson process. The presence of ionizing radiations is declared, if the total count exceeds or is equal to a threshold $\gamma_c$. The analysis is similar to that of the single sensor.
For the homogeneous WSN with N sensor nodes, the analytical expression for the probability of detection at the fusion centre in a given time T is derived as,

\[
\text{Global probability of detection} = \sum_{n_x \in \mathcal{C}} \text{poisson}(N(\lambda_1 + \lambda_2), T, n_x) \tag{3.10}
\]

\[
\text{Global probability of detection} = Q\left(\frac{\sqrt{\nu_c - N(\lambda_1 + \lambda_2)}}{\sqrt{N(\lambda_1 + \lambda_2)}}\right) \tag{3.11}
\]

Similarly, the mathematical expression for the global probability of false alarm is derived as,

\[
\text{Global probability of false alarm} = \sum_{n_x \in \mathcal{C}} \text{poisson}(N(\lambda_1), T, n_x) \tag{3.12}
\]

\[
\text{Global probability of false alarm} = Q\left(\frac{\nu_c - N(\lambda_1)}{\sqrt{N(\lambda_1)}}\right) \tag{3.13}
\]

where \[ Q(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{v^2}{2}} dv \]

These equations are arrived at using the normal approximation to the Poisson process and the Central limit theorem.

### 3.7.2 Threshold Design Equation for Decentralized Detection

In decentralized detection, each sensor compares its radiation count to a threshold, to arrive at a local decision about the presence of ionizing radiations. The \( i \)th sensor transmits the local binary decision \( I_i \) to the fusion
centre. The fusion centre evaluates the sum of the decisions $\Lambda$ and compares it against a threshold $\gamma_d$ to make a global inference.

The probability of the false alarm $p_{fi}$ and the probability of detection $p_{di}$ of the individual sensor node $S_i$ influence the detection performance. The probability of detection $p_{di}$ of sensor $i$ is the probability that the count exceeds a given threshold value.

The distribution of $\Lambda$ approaches a Poisson distribution with parameter $\lambda_3$ as examined in the simulation study which is shown in Figure 3.2, and it follows that,

$$\lambda_3 = E[\Lambda] = \sum_{i=1}^{N} E[I_i] = \sum_{i=1}^{N} p_{di}$$

(3.14)

Using the Normal approximation to Poisson distribution, the distribution of $\Lambda$ is given by, $\text{Normal}(\mu = \lambda_3, \sigma^2 = \lambda_3)$. The expression for the global probability of detection at the fusion centre is derived as

$$\text{Global probability of detection} = Q\left(\frac{\gamma_d - \lambda_3}{\sqrt{\lambda_3}}\right)$$

(3.15)

For this detection scheme, the global probability of false alarm is evaluated in a similar manner, and the mean and variance of Poisson distribution are computed as the sum of the false alarm probabilities of individual sensors.

$$\text{Global probability of false alarm} = Q\left(\frac{\gamma_d - \lambda_4}{\sqrt{\lambda_4}}\right)$$

(3.16)
where,

\[
\lambda_4 = \sum_{i=1}^{N} p_{fi}
\]  \hspace{1cm} (3.17)

**Figure 3.2** Simulation study of the Poisson test statistics. (Analytical – normal approximation to Poisson distribution)

### 3.7.3 Computational Complexity

In the centralized detection scheme, the only off-line computation required is the determination of a threshold to be used in the decision test by the fusion centre. The situation is more complex with the decentralized detection scheme, since the threshold must be computed for each sensor and for the fusion centre, and this computation is nontrivial.

For a WSN with \(N\) sensor nodes operating in the centralized mode, the number of thresholds to be computed is one. For a homogeneous WSN with \(N\) sensor nodes operating in the decentralized mode, the number of thresholds to be computed is two. And, for the corresponding heterogeneous WSN, the number of thresholds required to be computed is \((N+1)\). The threshold setting can be made dynamic based on the actual network
conditions. In this paper, the network conditions are assumed to be static and the thresholds are pre-computed before network deployment.

The threshold is designed such that the probability of detection $P_D$ is maximized for a given false alarm probability $P_{FA}$. The threshold design problem is a constrained nonlinear optimization problem, and this can be solved using the optimization toolbox in MATLAB®.

For the homogeneous WSN with $N$ sensor nodes employing a centralized operating option, the threshold is computed using equations (3.11) and (3.13) such that the global probability of detection is maximized for the given global probability of false alarm. For the homogeneous WSN with $N$ sensor nodes using a decentralized operating option, the threshold is computed using equations (3.14) to (3.17) such that the global probability of detection is maximized for the given global probability of false alarm.

On-line computation at the sensor nodes in the case of decentralized detection involves signal reception, processing and comparison with the threshold for making local decisions. On-line computation carried out at the fusion centre involves signal reception, processing and comparison with the threshold for making a global inference.

3.8 PERFORMANCE ANALYSIS

3.8.1 Performance of the Individual Sensor Node

The sensor detects the presence of the source when the number of photons detected in time $T$ is greater than or equal to some threshold $\tau$ as in equation (3.4). To understand the trade off between the probabilities of the
false positive and true positive, threshold $\tau$ is varied to determine the Receiver Operating Characteristics (ROC).

The ROCs of the individual sensor nodes are depicted in Figure 3.3(a) for T=0.1s, 0.5s, 1s and 5s, for the source radiation rate = 8, and the background rate =8. From these graphs, it is observed that the receiver operating characteristics improve with increasing T, and a greater threshold value gives a lower probability of false alarm, but also lowers the probability of detection.

The ROC shown in Figure 3.3(b) is for the source radiation rate = 2, and this corresponds to moving the sensor node further away from the radiation source. It is observed that the quality of the ROC is reduced, which means that there is a degradation in the detection performance if the sensor node is moved further away from the radiation source.

![Figure 3.3(a) Receiver Operating Characteristics for the source radiation rate = 8 and background rate = 8](image)

**Figure 3.3(a) Receiver Operating Characteristics for the source radiation rate = 8 and background rate = 8**
The four main parameters that influence $T$ are the false alarm probability, detector crystal area, background rate and the distance from the source to the sensor.

The plot of the time to detect ($T$) as a function of the distance between the source and the sensor, and the required probability of false alarm, is given in Figure 3.4(a) for a detector crystal area = 25 sqcm, background rate=8, and source rate=250. These curves illustrate the influence of the distance from the source to the sensor, and the required false alarm probability on the time taken by the sensor to make a decision. From these graphs, it is noticed that there is a significant increase in the time to detect ($T$) with an increase in the distance ($r$), and the rate at which the time $T$ increases with the distance is the highest for the lowest false positive value.

The graph of the time to detect ($T$) as a function of the detector crystal area ($A$) and the required probability of false alarm is depicted in Figure 3.4(b) for $r = 10$ meters, background rate=8 and source rate=250. From this figure, it is observed that the time to detect decreases with an
increase in the sensor detector crystal area and the time to detect becomes almost independent of the detector crystal area for \( A > 40 \text{cm}^2 \).

**Figure 3.4(a)** Time to detect as a function of distance and the probability of false alarm for the detector crystal area of 25 sqcm, background rate=8, source rate=250

**Figure 3.4(b)** Time to detect as a function of the detector crystal area and the probability of false alarm for \( r = 10 \) meters, background rate=8, source rate=250
The time to detect as a function of the distance from the source and the radiation rate are depicted in Figure 3.4(c). These results indicate that, if the distance from the source to the sensor is doubled, then the time to detect $T$ increases by a factor of 4, if every other parameter remains unchanged. If it is required to keep $T$ unchanged, then the sensitivity of the sensor, parameterized by the sensor area $A$ must be increased.

![Figure 3.4(c)](image)

**Figure 3.4(c) Time to detect as a function of distance and radiation rate for $A=49$ sqcm**

The time to detect as a function of the distance from the source and the background radiation rate are presented in Figure 3.4(d). From these results it is observed, that if the background intensity is twice the value, then the time to detect increases by a factor 2, with the other parameters remaining unchanged.
3.8.2 Performance Analysis of the Distributed Sensor System

The equations (3.10) to (3.17) derived for the global probability of detection and global probability of false alarm are non-linear functions of the sensor thresholds. For the prescribed global probability of false alarm, the equations are solved for the thresholds, such that the global probability of miss detection is minimized. The MATLAB® optimization tool is used for solving this non-linear constrained optimization problem.

To evaluate the performance of the WSN with decentralized detection, the design equations are solved to determine the required threshold for the prescribed false alarm probability. The simulation and analytical results are presented in Figure 3.5 for different node densities (N=4,6,8,10), and it is observed that the network detection performance improves with increased node density. For simulating the system, a simulation model is built.
by writing the appropriate code using the MATLAB command language. Using the model developed, simulation is executed for the specified simulation parameters (such as the seed value for random number generators and simulation length) and design parameters (such as the number of sensor nodes, node level probability of false alarm and detection probability). After the completion of the simulation, performance measures such as the system level probability of false alarm and the probability of detection are computed, and the results are displayed as a function of design parameters using a simulation postprocessor. Here, a routine for generating a plot is used, which takes the data created by simulation and generates the graphical output after formatting the data. This study also reveals the trade off between the network size, probability of detection and probability of false alarm.

Figure 3.5 ROC curve for different node densities for the system with the decentralized detection scheme

The detection performance of the WSN with centralized and decentralized detection schemes is evaluated for different design parameters, and the results are shown in Figure 3.6(a). For the centralized detection scheme, the detection performance of the system is studied for the range of
node densities \( N = 1, \ldots, 15 \) for different radiation rates \( (\lambda_1 = 8, \lambda_2 = 5) \), \( (\lambda_1 = 8, \lambda_2 = 2) \) and for the false alarm rates of 0.1 and 0.2. For the decentralized detection scheme, the detection performance is studied for the range of node densities \( N = 1, \ldots, 15 \) for different sensor parameters \( (p_{hi} = 0.95, p_{fi} = 0.1) \), \( (p_{hi} = 0.75, p_{fi} = 0.1) \). To understand the performance difference with the Chair-Varshney scheme, the system level probability of the detection as a function of the number of sensor nodes is shown in Figure 3.6(b). Here, the signal power is assumed to be twice as much as the noise power, \( p_{hi} = 0.75, p_{fi} = 0.1 \), and the system false alarm probability is fixed at 0.1. The main conclusions reached by studying these plots are summarized below:

- For a WSN with decentralized detection, the detection performance depends on the individual sensor detection probability. The higher the individual sensor hit rate, the better is the global detection performance. This can be observed in the characteristics curves with \( (p_{hi} = 0.95, p_{fi} = 0.1) \) and \( (p_{hi} = 0.75, p_{fi} = 0.1) \).

- For a WSN with the same design parameters, the network designed with a higher false alarm rate has an improved detection performance. This is indicated by the plots \( (\lambda_1 = 8, \lambda_2 = 2, PFA = 0.2) \) and \( (\lambda_1 = 8, \lambda_2 = 2, PFA = 0.1) \).

- For the same network size, the WSN with the centralized detection scheme performs well if the radiation photon rate is considerably high. This is confirmed by the plots \( (\lambda_1 = 8, \lambda_2 = 5, PFA = 0.1) \) and \( (\lambda_1 = 8, \lambda_2 = 2, PFA = 0.1) \).
For the specific system parameters used in this study, the centralized and decentralized detection schemes using the Neyman Pearson criteria out perform the system that uses the Chair-Varshney scheme.

**Figure 3.6(a)** Performance comparison of centralized and decentralized detection for different sensor and network parameters

**Figure 3.6(b)** Performance comparison of centralized and decentralized detection. $p_{hi} = 0.75$, $p_{fa} = 0.1$, and the system false alarm probability is fixed at 0.1
The Receiver Operating Characteristics of centralized and decentralized detection systems are shown in Figure 3.7 for different design parameters with $N=6$. The detection performance of the system is studied by varying the threshold, which gives rise to different detection probabilities. The main conclusions reached by analyzing these plots are summarized below:

- For a WSN with decentralized detection, the detection performance depends on the individual sensor detection probability. The higher the individual sensor hit rate, the better is the global detection performance. This can be observed in the characteristics curves with $(p_{hi} = 0.95, p_{fi} = 0.1)$ and $(p_{hi} = 0.75, p_{fi} = 0.1)$.

- For the same network size, the WSN with the centralized detection scheme performs well if the radiation photon rate is considerably high. This is confirmed by the plots $(\lambda_1 = 8, \lambda_2 = 5)$ and $(\lambda_1 = 8, \lambda_2 = 2)$.

- The performance depends mainly on the design parameters and not on the operating options.

![Figure 3.7 Receiver Operating Characteristics of centralized and decentralized detection](image)
The system level detection probability of the decentralized detection system (two sensor distributed detection scheme with mean background radiation count=10, source radiation count=0.625, measurement noise variance=10), is shown for the proposed scheme, for different false alarm probabilities in Figure 3.8. The detection performance of the system is compared with the detection scheme, considering spatial correlation (Ashok et al 2007). In this analysis, it is assumed that the probability of the hit rate and probability of the false alarm of individual sensors are set to $p_{hi} = 0.75$ and $p_{fi} = 0.1$, by appropriately selecting the local sensor decision thresholds. The proposed scheme is able to achieve a better detection performance for a smaller probability of false alarm (system level) and comparable performance at higher false alarm rates. This is appreciable, since in most of the practical situations, it is preferred to design distributed detection systems with lower false alarm rates.

![Figure 3.8 Performance comparison - Receiver Operating Characteristics](image)
### 3.8.3 Robustness to Node Failure

The resistance of the operating options of the wireless sensor network against node failure (destruction) is examined by computing the ratio of increase in the detection error probability $P_e$ when the number of failure nodes increases (Rajeev et al 2006). The ratio of increase in error probability for a wireless sensor network with 10 nodes is computed using the formula

$$\frac{P_e(K = i) - P_e(K = 10)}{P_e(K = 10)} \quad i = 1, 2, \ldots, 10 \quad (3.18)$$

Table 3.1 shows the ratio of increase in the error probability for the networks under assessment. To investigate the detection performance of the two operating options, the network parameters are fixed at $p_{hi} = 0.95, p_{f,i} = 0.1$ for decentralized detection, and the global false alarm rate is set at 0.1 for both the detection methods.

**Table 3.1 Ratio of increase in the error probability after node destruction**

<table>
<thead>
<tr>
<th>Number of node (failing)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decentralized</td>
<td>0.45</td>
<td>1.09</td>
<td>2.05</td>
<td>3.45</td>
<td>5.51</td>
<td>8.53</td>
<td>13.25</td>
<td>20.54</td>
<td>32.76</td>
</tr>
<tr>
<td>Centralized</td>
<td>1.00</td>
<td>3.50</td>
<td>8.75</td>
<td>20.00</td>
<td>44.25</td>
<td>95.25</td>
<td>202.25</td>
<td>423.00</td>
<td>877.50</td>
</tr>
</tbody>
</table>

Concerning the robustness to node failures, the loss of performance in terms of the ratio of increase in the error probability is the least for the decentralized detection option, and the highest for the centralized detection option. From Table 3.1 it is obvious, that the decentralized detection scheme is the most robust option against node failures.
Figure 3.9 shows the plot of the detection error probability versus the number of nodes for different network parameters. It is observed that the rate of increase in the error probability with node failure for decentralized detection depends on the detection performance characteristics of the individual node. The rate of increase in the error probability is higher, for the network with nodes which have better detection performance.

![Comparison of robustness](image)

**Figure 3.9 Comparison of robustness to node failures**

3.9 CONCLUSION

This chapter focuses on the class of design approaches to wireless sensor networks for the detection of ionizing radiations with signal processing perspectives. In this, the performance of the WSN designed for radiation detection using the Neyman Pearson methodology is investigated. The detection performance of the individual nodes and networks of sensor nodes under two different operating options for different network parameters and sensor characteristics are examined, and the results are presented to show the constraints and design trade offs that apply to the real world deployment of sensor nodes with radiation detection instruments.
From the analytical evaluation of the WSN designed for the detection of ionizing radiations, the following inferences were arrived:

- The ROC of a sensor node improves with increasing $T$, and a greater threshold value gives a lower probability of false alarm, but also lowers the probability of detection.
- The quality of the ROC of a sensor node is reduced, if the sensor node is moved further away from the radiation source.
- There is a significant increase in the time to detect ($T$) with an increase in the distance ($r$), and the rate at which the time $T$ increases with the distance is the highest for the lowest false positive value.
- The time to detect decreases with an increase in the sensor detector crystal area and the time to detect becomes almost independent of the detector crystal area for $A > 40 cm^2$.
- If the distance from the source to the sensor is doubled, then the time to detect $T$ increases by a factor of 4, if every other parameter remains unchanged. The sensitivity of the sensor, parameterized by the sensor area $A$ must be increased, if it is required to keep $T$ unchanged.
- If the background intensity is twice the value, then the time to detect increases by a factor 2, with the other parameters remaining unchanged.
- The network detection performance improves with increased node density.
- For a WSN with decentralized detection, the detection performance depends on the individual sensor detection probability. The higher the individual sensor hit rate, the better is the global detection performance.
- For a WSN with the same design parameters, the network designed with a higher false alarm rate has an improved detection performance.
• For the same network size, the WSN with the centralized detection scheme performs well if the radiation photon rate is considerably high.

• The detection performance of the WSN depends mainly on the design parameters and not on the operating options.

• The loss of performance in terms of the ratio of increase in the error probability is the least for the decentralized detection option, and the highest for the centralized detection option. Therefore, the decentralized detection scheme is the most robust operating option against node failures.

• The rate of increase in the error probability with node failure for decentralized detection depends on the detection performance characteristics of the individual node. The rate of increase in the error probability is higher, for the network with nodes, which have better detection performance.

It is expected that the results given would provide an insight for the optimal design of a WSN for radiation detection application. This study does not consider the physical characteristics of the containment systems that are designed to prevent the release of radiation into the environment. Further performance analysis considering the photon absorption rate in the medium will be worth investigating. Extension of this analysis to non ideal communication medium will be more useful.