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A Comprehensive Approach for Implementation of Randomly Deployed Wireless Sensor Networks

Nitika Rai and Rohin Daruwala
Veermata Jijabai Technological Institute, Mumbai, India - 400 019
Email: nitika75@yahoo.com; rddaruwala@el.vjti.ac.in

Abstract —Coverage analysis in WSN being a fundamental quality of service parameter needs utmost and precise assessment. Node sensing capability is a function of sensor characteristics and environmental factors which needs to be judiciously factored in sensing model used for coverage estimation. The probabilistic sensing models reported earlier consider only a certain subset of characteristics resulting in an incomplete sensing model. This paper employs a newly formulated and proposed model, *Composite Probabilistic Sensing Model* (*CPSM*) that cumulates all possible effects. Typically, nodes are prone to failures during deployment phase itself due to manufacturing defect, severe environmental condition or physical damage. Such node failures should also be addressed for coverage analysis. In addition, during network operation, harsh weather conditions and overloading may lead to early death of certain nodes making the network dysfunctional when 1-coverage is opted. To offer better network reliability, and to cater to increased sensitivity of critical applications, network designers opt for *k*-coverage. Hence, this paper focuses on investigation of estimation of node density for varied coverage requirements. It also includes a parametric study of effect and dependency of various factors on the required node density. This results in a comprehensive study that aid in WSN design/ analysis/ implementation.

Index Terms—Wireless sensor network, random deployment, probabilistic sensing model, *k*-coverage, node density estimation

I. INTRODUCTION

Wireless Sensor Networks (WSN) have gained significant attention resulting in a plethora of research activities due to its ability to offer an extensive range of monitoring based applications that includes environment, structural health, traffic, pollution control, smart houses and target tracking and rescue mission based applications like battlefield surveillance and fire detection system to name a few [1]-[3]. Most of the reported work is focused towards achieving Quality of Service (QoS), namely lifetime, throughput, reliability, scalability and latency. During investigation of the said parameters, it is assumed that the nodes deployed in the network area are adequately large in number, which is a wrong assumption and may result into misleading conclusions and increased system cost [1], [4]. Hence, an optimal WSN design as a first step must determine the adequate number of nodes necessary to provide either temporal or spatial requirements in terms of coverage as per the application [1], [2], [5]-[8].

This parameter is quantified by the term *Network coverage* and is considered as a fundamental and critical QoS parameter [2], [9], [10]. Network coverage is a measure of the percentage fraction of the total network area that is covered collectively by the deployed nodes [4], [5], [9]-[13]. In parallel, the issue that needs to be addressed is the deployment strategy which also affects the node density requirement. The deployment strategy can be either deterministic or random - the selection based on the application and accessibility to the network area. Deterministic deployment is mostly suited when there is an ease of access to the network area or in a controlled environment while random deployment is an evident choice for hostile environments [1], [9], [13], [14]. It is also to be noted that the nodes deployed typically have a limited sensing range. Hence, the optimal number of nodes needed to attain the required network coverage is dependent on the choice of the deployment strategy and on the sensing capability of the nodes.

Node sensing capability can be modeled using sensing models and have been extensively reported in the literature. Sensing models are vital to estimate and evaluate network coverage and connectivity; carry out redundancy analysis and investigate node scheduling and intruder detection algorithms [15]-[23]. Comparison of the sensing models has also been studied [10], [11]. The simplest sensing model typically used for coverage analysis assumes a disk based binary sensing model [5], [11]-[13], [19]-[26]. However, in practice, sensing is non-uniform which can be attributed to the characteristics of the sensing device characteristics and environmental conditions which are stochastic in nature. Hence, probabilistic sensing models are used to take into account these parameters. These models estimate the effective sensing radius of a node and thereafter can be used to predict percentage coverage fraction.

The probabilistic sensing models previously reported in the literature either factors device characteristics only [5], [11], [13], [26]-[30] or environmental conditions alone [10], [24], [31]-[33] making the use of the same unrealistic and misleading. The need of a realistic sensing model is much felt and has not been satisfactorily reported [7], [13], [26], [34]. Hence, we propose a novel model, namely *Composite Probabilistic Sensing Model* (*CPSM*) which includes the cumulative effect of all stochastic parameters possible.

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Corresponding author email: nitika75@yahoo.com.
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Additionally, there are certain other aspects related to network design that need attention specifically in randomly deployed networks. Firstly, node failures during deployment which are an inevitable phenomenon have not been addressed for network coverage analysis. Nodes are prone to be damaged/ become non-functional during deployment phase itself due to manufacturing defect, severe environmental condition or physical damage. Node failure probability can be high and may result in a reduction of effective network coverage. Hence, it is imperative to assess network coverage considering node failure as a parameter [1], [2], [8], [35]. Also, owing to severe weather conditions, harsh physical environment, wear and tear or over-loading of working nodes, some nodes tend to die out earlier than their expected lifetime causing coverage voids within the network and often decreasing the lifetime of the network. This may lead to network becoming dysfunctional much before expected when 1-coverage is opted. Hence, network designers need to consider *k*-coverage. *k*-coverage is specifically necessary and important for mission critical applications, such as intrusion detection, data gathering, object tracking and desirable in situations where a stronger monitoring capability is required, such as military applications. Networks with a higher coverage degree can obtain higher sensing accuracy and be more robust, thus guarantee network reliability and accuracy [7]-[9]. *k*-coverage basically introduces redundancy and can affect the performance and the cost of the system drastically [34]. Various works on *k*-coverage attainment and node scheduling have been reported [36]-[52] but the initial estimation of required number of nodes for *k*-coverage have not been considered in any of the reported work. Hence, these two aspects – consideration for node failures and *k*-coverage attainment need to be included for estimating the optimum density of nodes to enhance coverage robustness and network reliability.

Hence, this paper carries out an investigation of required node density for all varied coverage requirements. It essentially focuses to extend the mathematical modelling of the proposed model - *CPSM* to include node failures and *k*-coverage. It further includes a parametric study of effect of node failures and *k*-coverage as a function of sensing device characteristics, environmental factors and desired coverage fraction. These results can be used to estimate the density of sensor nodes needed to be randomly deployed in order to achieve the desired coverage fraction with the required network robustness and accuracy as per the application. The results presented in the paper can aid in WSN design/ analysis /implementation.

The organization of the rest of the paper is as follows. Section II discusses the classification of WSN design considerations. Sections III present the probabilistic sensing model – *CPSM*, its mathematical modelling and further its extension to factor node failures and *k*-coverage. It also includes the simulation setup and the adopted methodology used for numerical analysis. Section IV present the numerical results and investigation of the impact of node failure on the required density of nodes to achieve a given coverage fraction with *k*-coverage. Extensive parametric analysis is also carried out to study the effect and dependency of environmental factors, device parameters, required coverage fraction, coverage degree and node failures on the required node density. Finally, Section V concludes the paper.

II. DESIGN CONSIDERATIONS

The comprehensive approach to design/ analyze/ implement WSN involves certain design consideration as illustrated in Fig. 1.

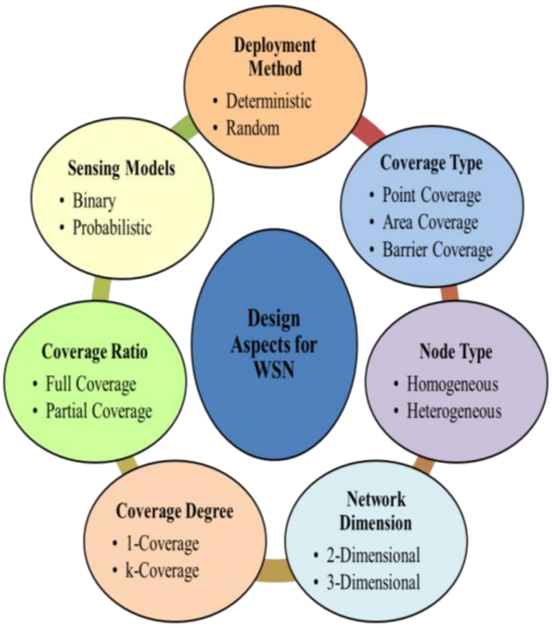


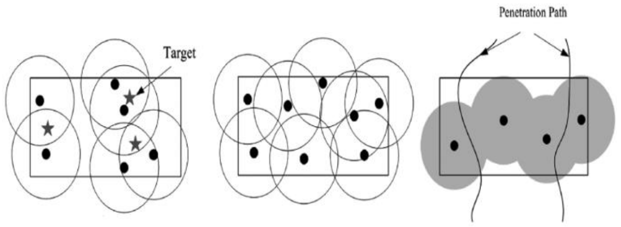
Fig. 1. WSN design considerations

A. Depoyment Method

The deployment method adopted can be random or deterministic. The choice depends on the application, ie. its criticality, the terrain and the expanse of the network. The choice affects the deployment cost and time. Random deployment is more suited in hostile and inaccessible area or when the expanse is very large. The nodes are either dropped from an aircraft or launched using artillery shells [1], [4], [8], [9], [13], [14]. It results in an uneven density of nodes in the network area and causes node failures. The initial nodes failure could be high and needs consideration. Hence, the utmost challenge is to guarantee a sufficient number of nodes so that the required network coverage is achieved. Deterministic node deployment involves placing nodes at pre-defined locations in the network in controlled environment or for critical applications. Though such schemes are optimal, it is impractical to carefully position the nodes in large scale WSNs.

B. Coverage Type

Coverage type refers to the subject to be covered by a sensor network. It can be classified into three types, namely, point coverage, area coverage and barrier coverage [7], [17], [34], [53]. In point coverage problem, the subject to be covered is a set of discrete points (Fig. 2 (a)). These points can be some particular space points to represent the sensor field or are used to model some physical targets in the sensor field. The objective is to find the optimal locations to place sensor nodes to minimize network cost. In the area coverage problem, the subject to be covered is the whole sensor field (Fig. 2 (b)). The objective is to find the least number of nodes per unit area to provide complete coverage for the whole sensor field. Barrier coverage involves the coverage problems of building intrusion barriers for detecting intrusions of a mobile object when it traverses from one side to the other side of the sensor field (Fig. 2 (c)). The trajectory of an intrusion mobile object is called its traverse path. The objective is to enable the covered points to form an intrusion barrier, stretching across the sensor field and intersecting with every potential traverse path.



(a) (b) (c)

Fig. 2. (a) Point (target) coverage (b) Area coverage (c) Barrier coverage

C. *Node Types*

Sensor networks can be classified into two types: homogeneous and heterogeneous. Homogeneous networks comprises of all nodes being identical in terms of battery energy, functionality and hardware complexity while heterogeneous networks consist of nodes with varied capabilities. Some nodes are more powerful than other nodes. Alternatively, nodes can also be classified as being static or mobile. Static nodes imply that they remain stationary once they are deployed. Mobile nodes have the capability to move after deployment in order to improve the performance of the WSN.

D. *Coverage Area Dimension*

The placement of the nodes in the network area can be in two-dimensional (2D) plane or in three dimensional (3D) space. 3D sensor network is used generally for underwater surveillance or for air pollution monitoring by using floating lightweight sensors in air and space.

E. *Coverage Degree*

Coverage degree describes how a point is covered. The minimum and most optimized approach is that every point in the network must be covered by atleast one node. This is called as 1-coverage model. Specifically, for random deployment, node failures occur during deployment phase itself due to physical damage and harsh physical environment. Also, during operation, severe weather conditions and overloading can lead to premature death of the node. Hence, depending on the criticality of the application, it may become crucial that each physical point is covered by atleast k different nodes. This constraint is known as k-coverage and it helps to improve coverage robustness.

F. *Coverage Ratio*

Coverage ratio (or, coverage fraction) is an application related parameter and measures the effective area covered by all the nodes in the given network. The achievable percentage coverage for randomly deployed nodes is an exponential function (as derived in later section). Hence, to attain 100% coverage (full-coverage), the required number of nodes is bound to be very high which for most of the applications may result in high degree of redundancy not worth the cost [5], [8], [11], [12]. Hence, it is appropriate to consider partial coverage as per the requirement of the application to design a practical WSN system.

G. *Sensing Models*

Sensing models are used to mathematically represent the limited sensing range of the nodes. These are broadly classified into two types – Deterministic sensing model and Probabilistic sensing models.

Deterministic sensing model assumes the sensing capability of the node to be binary in nature wherein an event can be detected as long as it is at a distance of less than R_s from the center of the node, where R_s is the maximum sensing radius of the node [5], [11], [17], [19]-[21], [26]. This model is hypothetical and does not take into account the device characteristics which may result in uneven sensing and environmental factors that may lead to non-uniform sensing. Since these factors are stochastic, probabilistic sensing models are proposed to factor these parameters.

There are various probabilistic sensing models presented in the literature. One set of model are based on the concept that the sensing capability of the nodes degrades as a function of the distance from the center of the node and the sensing device characteristics. The degradation can be exponential [16], [28], [30], [54]-[57], cubic [26], [29] or in a staircase pattern [32], [54]. The other concept is that the degradation of sensing capability is a function of the shadowing effect and is based on the log normal shadowing path loss model which is dependent on the power emitted by the node and the environmental conditions in which the node operates [5], [10], [11], [24], [31]-[33], [58]-[60]. Few others reported include truncated attenuated disk model [8], [17], [22], irregular sensing model [60], [61] and directional sensing model [35].

Sensing models can be used to estimate the network coverage achieved by a given set of nodes or alternatively can be used as a design parameter to estimate the number of nodes needed to provide the desired network coverage fraction [23], [26].

III. METHODOLOGY AND MATHEMATICAL MODELING

A. *Composite Probabilistic Sensing Model (CPSM)*

CPSM essentially considers all stochastic factors that can possibly affect the sensing capability of a node. Practically, the parameters that can affect this maximum sensing radius of a node are the device characteristics which dictates the rate of decrease of sensing capability of the node as a function of the distance from the center of the node and the environment related factors that essentially take into account the propagation loss owing to obstructions leading to shadow fading effect in various environmental conditions.

The sensing device characteristics can be modeled using device parameters δ and μ which signifies the physical properties of the node. Let R_s and R_m be the maximum sensing radius and distance from center of node at which uncertainty in detection persists respectively. Hence, the event detection probability at a distance z from the center of the node can be defined as given in (1) [5], [11], [62].

$$p(z) = \begin{cases} 1, & 0 \le z \le R_m \\ e^{-\mu(z-R_m)^{\delta}}, & R_m < z < R_s \\ 0, & z > R_s \end{cases} \tag{1}$$

To model environmental factors, we assume log normal shadowing path loss model [24], [31], [32], [63]. Let the event generate power, P_o and the mean path loss occurring at a reference distance of d_r be $PL(d_r)$, then the signal power received by the node can be given as,

$$P_r(z) = P_o - PL(d_r) - 10n\,log_{10}\left(\frac{z}{d_r}\right) + \chi_\sigma \tag{2}$$

where, n is termed as the path loss exponent that represents the rate at which the signal power decreases with distance and χ_σ is a Gaussian random variable (in dB) with zero mean and variance, σ^2.

The threshold power of the node which signifies the node sensing sensitivity is given by

$$P_{r-th} = P_o - PL(d_r) - 10n\,log_{10}\left(\frac{R_e}{d_r}\right) \tag{3}$$

where, R_e is the average sensing radius of the node.

Event detection is possible by the node when $P_r(z) > P_{r-th}$. Hence, the probability of event detection at a distance z from the center of the node is given as [24], [31], [32], [63].

$$\begin{aligned} p(z) &= Prob(P_r(z) > P_{r-th}) \\ &= Prob\left(\chi_\sigma > 10nlog\left(\frac{z}{R_e}\right)\right) \end{aligned} \tag{4}$$

Given that χ_σ is a Gaussian random variable with zero mean and variance, σ^2,

$$\begin{aligned} p(z) &= \int_{10nlog_{10}\left(\frac{z}{R_e}\right)}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(\frac{z^2}{2\sigma^2}\right)}.dz \\ &= Q\left(\frac{10nlog_{10}\left(\frac{z}{R_e}\right)}{\sigma}\right) \end{aligned} \tag{5}$$

The value of n is used to represent different types of environment. It typically has the value in the range from 2 to 6 as shown in Table I.

TABLE I: PATH LOSS EXPONENTS FOR DIFFERENT ENVIRONMENTS [63]

Environment	Path loss exponent, n
Free space	2
Urban area	2.7-3.5
Shadowed urban area	3-5
In building line of sight	1.6-1.8
Obstruction in building	4-6
Obstruction in factories	2-3

It is to be noted that n can also take different values in line of sight (LOS) and non-line of sight (NLOS) scenarios in the same environment [5], [10], [31]. When LOS exists, $n = n_{min} = 2$ and then the sensing radius attains the maximum value, i.e. R_s.

Hence, the average sensing radius can be computed as

$$R_e = d_r \left[\frac{R_s}{d_r}\right]^{\frac{n_{min}}{n}} \tag{6}$$

As reported earlier, the standard deviation, σ can be strongly related to path loss exponent, n [5], [10], [31]. In non-shadowing environment, i.e. when $n = 2$ and $\sigma = 0$, the sensing radius attains its maximum value, i.e. $R_e = R_s$, considering $d_r = 1$m. For a particular environment, the small variations of path loss exponent can be represented as effect of σ (shadowing) while keeping n constant. Equation (6) can then be used to compute the normalized sensing radii, (R_e/R_s). A few sample computations used in this paper are tabulated in Table II.

TABLE II: NORMALIZED SENSING RADIUS FOR VARIOUS SHADOWING ENVIRONMENT

σ	(R_e/R_s)				
	R_s =10m	R_s =15m	R_s =20m	R_s =25m	R_s =30m
0 dB	1	1	1	1	1
2 dB	0.896	0.879	0.867	0.858	0.851
4 dB	0.811	0.782	0.761	0.746	0.734
6 dB	0.741	0.702	0.677	0.657	0,642
8 dB	0.681	0.637	0.607	0.585	0.567

The *Composite Probabilistic Sensing Model* states that the probability of event detection by a node at a distance z from the center of the node can be expressed as shown in (7).

In the range, $R_m < z < R_s$, we can compute the threshold distance, R_t by plotting the curves using (1) and (5) for the given values of environmental factors and sensing device characteristics. To illustrate, the plot of probability of detection as a function of sensing range for $R_s = 20$m, $R_m = 0$ and for a few sample values of device

$$p(z) = \begin{cases} Q\left(\dfrac{10n\log_{10}\left(\frac{z}{R_e}\right)}{\sigma}\right), & 0 \le z \le R_m \\ \min\left\{e^{-\alpha(z-R_m)^{\gamma}}, Q\left(\dfrac{10n\log_{10}\left(\frac{z}{R_e}\right)}{\sigma}\right)\right\}, & R_m < z < R_s \\ 0, & z > R_s \end{cases} \quad (7)$$

characteristics and environmental factors are as shown in Fig. 3. It can be concluded that for a given sensing characteristics and environmental parameters in a real world scenario, there exists a threshold distance from the center of the node, R_t beyond which the effect of environmental factors becomes dominant. The device parameters degrade the probability of detection more towards the interior of the node and environmental factors towards the periphery. It is to be noted that if $R_m = R_t$, the effect of device parameters can be neglected.

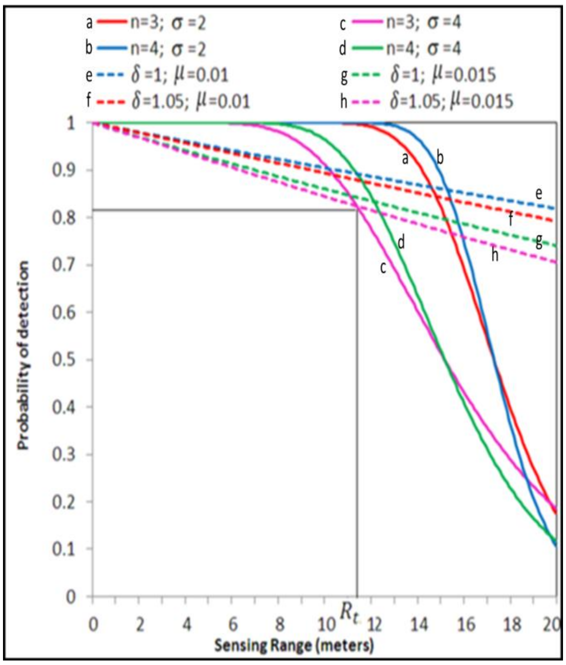


Fig. 3. Probability of detection as a function of sensing range considering R_s =20m and R_m =0

B. Network Coverage

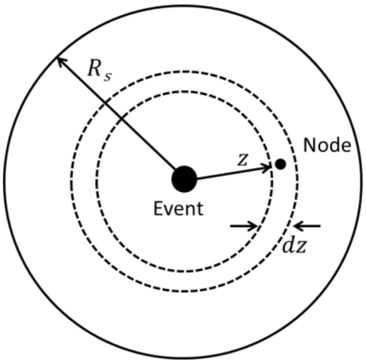


Fig. 4. Detection scenario for probabilistic sensing model

Network coverage can be mathematically modeled using probability theory. Consider that N_s number of sensor nodes are randomly deployed over an area, A_N. The probability of presence of a specific node at a distance z to the event is $2\pi z dz/A_N$, where dz represents a infinitesimally small increment in z (Fig. 4).

Then, probability that the node senses the event is given by [5], [10], [11], [31].

$$P_d = \frac{1}{A_N}\int_0^{R_s} p(z)2\pi z.dz \quad (8)$$

Hence,

$$P_d = \frac{1}{A_N}\left\{ \begin{array}{c} \displaystyle\int_{z=0}^{R_m} Q\left(\frac{10n\log_{10}\left(\frac{z}{R_e}\right)}{\sigma}\right) \\ \displaystyle + \int_{z=R_m}^{R_t} e^{-\mu(z-R_m)^{\delta}}.2\pi z dz \\ \displaystyle + \int_{z=R_t}^{R_s} Q\left(\frac{10n\log_{10}\left(\frac{z}{R_e}\right)}{\sigma}\right).2\pi z dz \end{array} \right\} \quad (9)$$

Full sensing coverage can be achieved provided that every point in the network area lies within the sensing area of at least one node. Hence, coverage fraction can be defined as the probability of an event being detected by at least one node, ie. for coverage degree, k = 1 and is given by [5], [11], [64]

$$\begin{aligned} C_f &= \sum_{k=1}^{N_s}\binom{N_s}{k}{P_d}^k(1-P_d)^{N_s-k} \\ &= 1-\left(\binom{N_s}{0}{P_d}^0(1-P_d)^{N_s}\right) \\ &= 1-(1-P_d)^{N_s} \end{aligned} \quad (10)$$

For k = 2, coverage fraction can be defined as the probability of an event being detected by atleast two nodes and is given by

$$\begin{aligned} C_f &= 1-\left(\sum_{k=0}^{1}\binom{N_s}{k}{P_d}^k(1-P_d)^{N_s-k}\right) \\ &= 1-(1-P_d)^{N_s}-N_sP_d\,(1-P_d)^{N_s-1} \end{aligned} \quad (11)$$

Similarly, for k = 3, coverage fraction can be given by

$$\begin{aligned} C_f &= 1-\left(\sum_{k=0}^{2}\binom{N_s}{k}{P_d}^k(1-P_d)^{N_s-k}\right) \\ &= \left\{ \begin{array}{c} (1-P_d)^{N_s}-N_sP_d\,(1-P_d)^{N_s-1} \\ -\dfrac{N_s(N_s-1)}{2}{P_d}^2(1-P_d)^{N_s-2} \end{array} \right\} \end{aligned} \quad (12)$$

The above analysis assumes that all the nodes are functional post deployment. However, in practice and in a realistic scenario, nodes are prone to failures during deployment phase itself due to manufacturing defect, severe environmental condition on site or physical damage. Such node failure probability could be high and need a consideration while estimating optimum density of nodes to be deployed in order to ensure adequate coverage and enhance coverage robustness.

C. k-Coverage with Consideration for Node Failures

We know that the probability of any event in A_N of being detected by a non-faulty node is given by P_d. The event remains undetected by the node if the event does not occur within the sensing radius of the node or it does occur but the node is faulty. If P_{nf} be the probability of node failure, the probability that the event will not be detected by a node is given by

$$\begin{aligned} P_{un-d} &= (1-P_d) + P_d . P_{nf} \\ &= \left[(1-P_d(1-P_{nf})\right] \end{aligned} \quad (13)$$

The probability that the event remains undetected by any of the N_s sensor nodes is

$$P_{un-d_{N_s}} = \left[(1-P_d(1-P_{nf})\right]^{N_s} \quad (14)$$

Hence, for $k = 1$, coverage fraction is given by

$$C_f = 1 - P_{un-d_{N_s}} = 1 - \left[(1-P_d(1-P_{nf})\right]^{N_s} \quad (15)$$

Similarly, for $k = 2$ and $k = 3$, coverage fraction is as given in (16) and (17) respectively.

$$C_f = 1-(1-p)^{N_s} - N_s p\,(1-p)^{N_s-1} \quad (16)$$

$$C_f = \left\{ \begin{array}{c} 1-(1-p)^{N_s} - N_s p\,(1-p)^{N_s-1} \\ -\dfrac{N_s(N_s-1)}{2} p^2 (1-p)^{N_s-2} \end{array} \right\} \quad (17)$$

where, $p = P_d\,(1 - P_{nf})$.

D. Network Simulation Model

The network simulation model comprises of homogeneous nodes of maximum sensing radius of R_s being deployed randomly with uniform distribution in a two dimensional field of network area, A_N. Numerical analysis is carried out using Matlab to estimate the density of nodes required to be deployed to achieve desired coverage fraction (75%-95%) considering *k*-coverage and/or node failures. However, the methodology adopted for partial coverage holds good for 100% coverage as well. The parameters chosen to carry out simulations are summarized in Table III. Further, investigation on the effect of node failure and coverage degree on the required density of nodes is carried out which includes an extensive parametric study to examine the effect of sensing device characteristics and environmental factors. These results can be used to predict the density of randomly deployed nodes needed for a desired coverage fraction with the required network robustness and accuracy as per the application and this can aid in WSN design/ analysis/ implementation.

TABLE III: SIMULATION PARAMETERS

Parameters	**Values**
Deployment method	Random
R_s	10m, 15m, 20m, 25m, 30m
R_m	0
α	0.01, 0.015, 0.03
γ	1, 1.05
σ	2, 4, 6, 8
n	3, 4
k	1, 2, 3
P_{nf}	0, 0.10, 0.20

IV. RESULTS AND DISCUSSION

Numerical analysis for computation of required node density to achieve various network coverage fraction is carried out in Matlab for different combinations of values of R_s, μ, δ, σ and n. One such numerical result as a sample for R_s = 10m with n = 4, δ = 1, μ = 0.01 and σ = 4 for different values of k and P_{nf} is as shown in Fig 5. It is observed that there is a substantial increase in the required number of nodes to achieve a higher coverage degree for a given network coverage fraction. However, it is very important to observe that the percentage increase in the required density of nodes is a function of desired network coverage fraction.

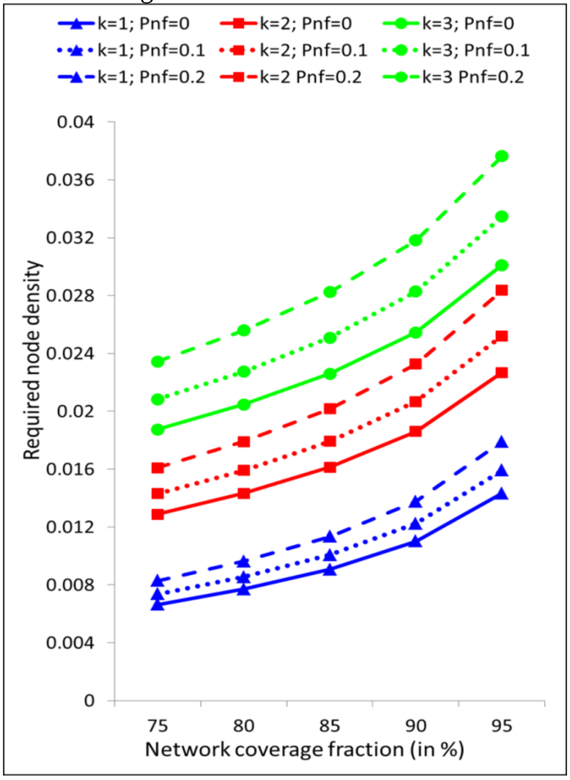


Fig. 5. Network coverage fraction (in %) vs required node density for R_s =10m; k=1, 2, 3; P_{nf} = 0

Fig. 6 shows the variation in percentage increase of density of nodes as a function of network coverage fraction when network coverage is enhanced from k = 1 to 2 and k = 2 to 3. When k = 2 is desired, the required number of nodes increases by about 94% at C_f = 75% coverage fraction but requires 58% increase in required number of nodes while aiming for C_f = 95% coverage fraction. This difference can be explained due to the redundancy already introduced while trying to achieve higher coverage fraction with k = 1. However, the slope of variation with respect to network coverage fraction is much lower when aiming to achieve k = 3 from k = 2. This can be justified on similar lines as above that redundancy which is already factored for higher coverage degree also contributes to attainment of high coverage fraction.

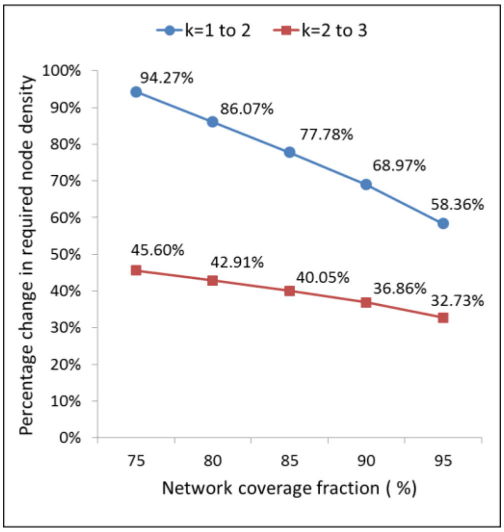


Fig. 6. Variation in percentage increase of density of nodes as a function of C_f when k is enhanced

Hence, we conclude that the desired coverage degree must be sought for as per the requirement of the application as it can lead considerable increase in the required number of nodes and thus to a substantial increase in the network cost.

The impact of node failure on the required density of nodes to achieve a desired coverage can also be observed from Fig. 5. For 10% node failure, the expected redundancy is about 11% and for 20% node failure, it is about 25% to achieve the same coverage fraction. This holds true for any coverage degree. Hence vulnerable scenarios call for deployment of redundant nodes which increases the network cost considerably. However, some applications which are critical as well as vulnerable may require considering both higher coverage degree while simultaneously factoring node failures for computation of number of nodes to be deployed. Effect of node failures and higher order coverage degree is shown in Fig. 7. It can be observed that the increase in percentage change of required nodes is linear as a function of network coverage fraction and is dependent on the value of k and probability of node failure. The slope is steeper when coverage degree is increased from k = 1 to k = 2, ie. the variation of percentage increase as a function of network coverage fraction is higher as compared to when coverage degree is increased from k = 2 to k = 3. Also, the effect node failure is also higher when coverage degree is increased from k = 1 to k = 2 than when coverage degree is increased from k = 2 to k = 3. However, the variation is independent of coverage fraction.

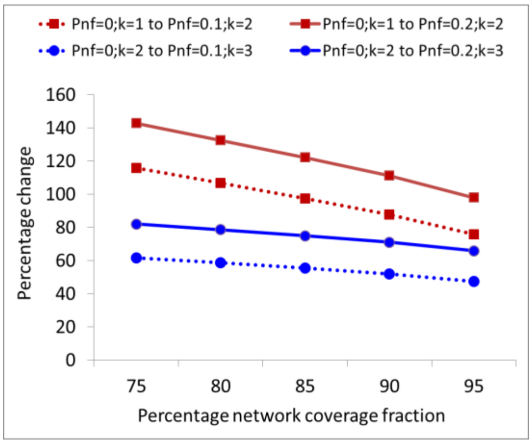
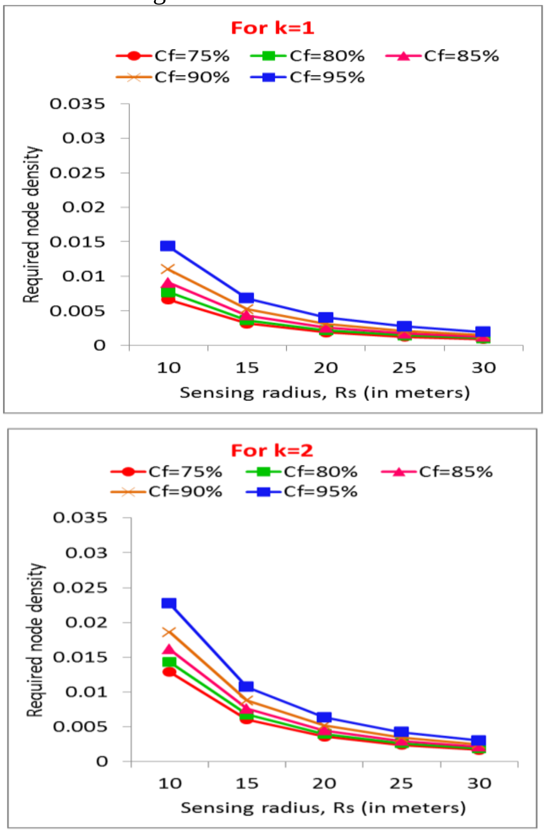


Fig. 7. Increase in percentage change of required nodes as a function of C_f when k and P_{nf} changes

We further carry out a parametric analysis to investigate the effect of various stochastic parameters. The following are the observations –

- *Effect of* R_s : To illustrate, as a sample, the required density of nodes as a function of sensing radius to achieve the desired coverage fraction considering μ = 0.01, δ = 1, σ = 4 and n = 4 for different k-coverage is as shown in Fig. 8.



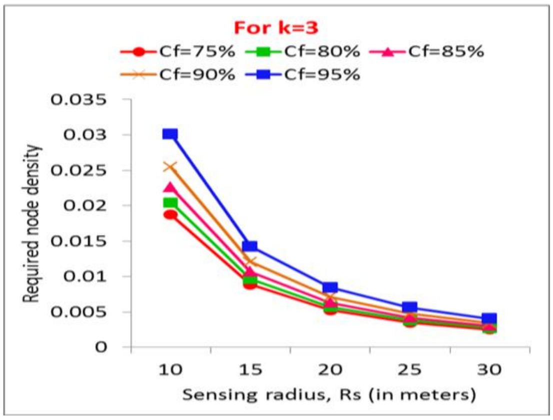


Fig. 8. Required density of nodes as a function of sensing radius considering $\mu = 0.01$, $\delta = 1$, $\sigma = 4$ and $n = 4$ for different k-coverage

It is observed that the required density of nodes reduces with increase in R_s. The percentage decrease in the required node density for a given coverage fraction as R_s varies is as shown in Fig. 9. Additionally, Table IV summarizes the results with varying R_s, μ and σ while $\delta = 1$ and $n = 4$ are kept constant. It is observed that the percentage decrease is slightly lesser with degradation in device characteristics for similar change in value of R_s. However, as the shadowing effect becomes more prominent, the effect is dependent of the corresponding value of device characteristics. For $\mu = 0.01$, percentage decrease slightly reduces as σ increases while when $\mu = 0.03$, the percentage decrease slightly increases as σ increases.

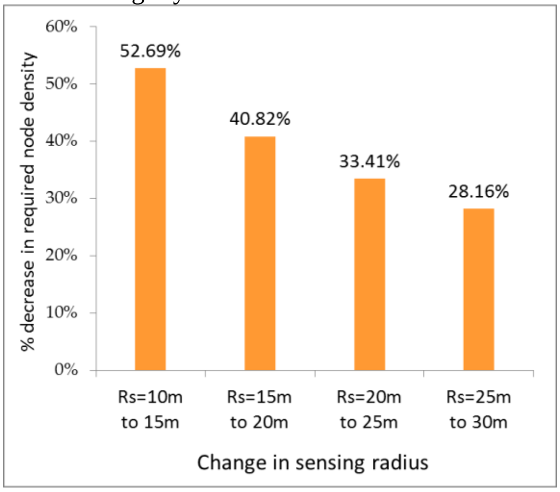


Fig. 9. Percentage decrease in required node density for any coverage fraction as R_s varies

- *Effect of μ*: The effect of μ on the required node density for different values of R_s and σ while μ is varied from 0.01 to 0.03 is as shown in Table V. It can be observed that as μ increases, there is a rise in required node density. However, the increase percentage is dependent on the value of R_s and σ. The percentage increase reduces to half for every incremental increase of σ by 2 for a given R_s. Also, for a given value of σ, the percentage increase becomes higher as R_s increases.

TABLE IV: DECREASE (IN %) IN REQUIRED NODE DENSITY WITH VARYING R_S, μ AND σ AND WITH $\delta = 1$AND $N = 4$ KEPT CONSTANT AND CONSIDERING $P_{NF} = 0$

		R_s = 10m to 15m	R_s = 15m to 20m	R_s = 20m to 25m	R_s = 25m to 30m
μ =0.01	σ =2	53.4%	41.4%	33.7%	28.4%
	σ =4	52.7%	40.8%	33.4%	28.2%
	σ =6	51.9%	40.5%	32.8%	27.7%
	σ =8	51.5%	39.9%	32.5%	27.2%
μ =0.03	σ =2	51.2%	38.7%	30.5%	24.8%
	σ =4	51.3%	39.0%	31.1%	25.7%
	σ =6	51.3%	39.4%	31.4%	26.0%
	σ =8	51.4%	39.3%	31.8%	26.4%

TABLE V: INCREASE (IN PERCENTAGE) IN REQUIRED NODE DENSITY WITH VARYING R_S AND σ WHILE μ VARIES FROM 0.01 TO 0.03 AND N=4, δ=1KEPT CONSTANT AND CONSIDERING $P_{NF} = 0$

R_s		10m	15m	20m	25m	30m
Percentage increase in node density	σ=2	8.2%	13.1%	18.3%	24.1%	30.4%
	σ=4	4.4%	7.3%	10.5%	14.4%	18.5%
	σ=6	2.2%	3.7%	5.6%	7.8%	10.3%
	σ=8	0.9%	1.7%	2.7%	3.8%	5.1%

TABLE VI: INCREASE (IN PERCENTAGE) IN REQUIRED NODE DENSITY WITH VARYING R_S AND Σ WHILE μ=0.01, N=4, δ=1 KEPT CONSTANT AND CONSIDERING $P_{NF} = 0$

		10m	15m	20m	25m	30m
μ=0.01	σ= 2 to 4	16.8%	18.5%	19.8%	20.3%	20.7%
	σ= 4 to 6	13.3 %	15.1%	15.7%	16.8%	17.6%
	σ= 6 to 8	10.6%	11.5%	12.7%	13.1%	13.8%
μ=0.03	σ= 2 to 4	12.7%	12.4%	11.9%	10.9%	9.6%
	σ= 4 to 6	11.8%	11.2%	10.5%	10.1%	9.5%
	σ= 6 to 8	9.9%	9.6%	9.3%	8.9%	8.3%

- *Effect of σ*: The effect of σ on the required node density for different values of R_s and μ while σ is varied is as shown in Table VI. It is observed that as the shadowing effect deepens, there is a reduction in the percentage increase of required node density. However, for a similar variation in σ, as R_s increases, the percentage increase is more. Also, there is reduction in percentage increase with deterioration in device characteristics.
- The trends and findings cited and discussed above (ie. considering effect of R_s, μ, σ) holds true for any coverage degree. All of these were analyzed considering that there are no node failures. Factoring node failures result in introduction of additional redundancy of 11.1% when $P_{nf} = 10\%$ is factored and of about 25% when $P_{nf} = 20\%$ is considered.
- Another interesting observation is noted when the effect of desired coverage fraction is analyzed. The percentage increase in required node density for each incremental increase of 5% in coverage fraction is as shown in Fig. 10 for varied coverage degree (ie. k = 1, 2, 3). The percentage increase is much lesser when

expected coverage fraction increases from 75% to 80%. However, it is much higher when change in coverage fraction happen at the higher end. Also, effect of coverage fraction is more pronounced for *k* = 1 and lowers as *k* increases. This behavior is identical for any combination of environmental factors and device characteristics existing in a realistic scenario.

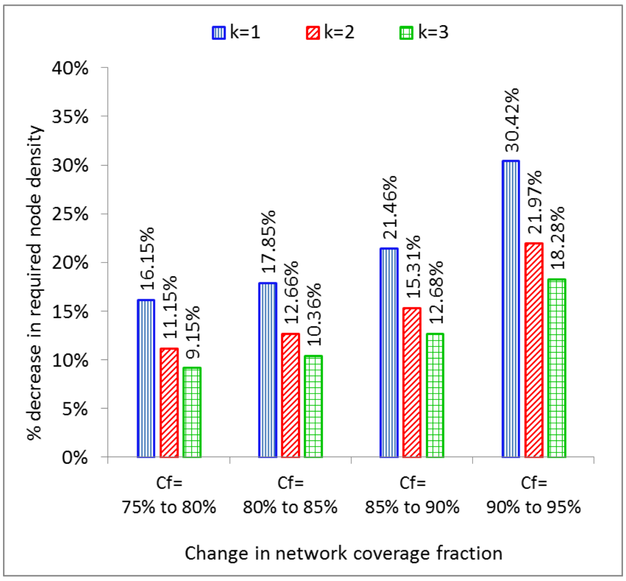


Fig. 10. Percentage decrease in required node density as coverage fraction varies

V. CONCLUSIONS

One of the prime and fundamental quality of service parameter in WSN is network coverage. Coverage estimation analysis is based on node sensing capability which in turn is dependent on parameters like sensor characteristics and environmental factors. In addition, node failure during deployment phase is an inevitable phenomenon. Also, certain critical applications require higher degree of coverage to provide enhanced sensing accuracy and be more robust in order to guarantee better network reliability. None of the probabilistic sensing models reported have considered the cumulative effect of all these parameters. Hence, this paper focuses on a model proposed by the authors in their previous work which combine the cumulative effects of all possible stochastic parameters into a single sensing model, called *Composite Probabilistic Sensing Model* (*CPSM*) and further now its extension to factor node failures and *k*-coverage to finally present a comprehensive study for coverage evaluation and estimation of required number of node. A detailed investigation of required node density for all varied coverage requirements is presented. Additionally, parametric study of effect of node failures and *k*-coverage as a function of sensing device characteristics and environmental factors is also included. The results presented here can aid in precise assessment of required node density during WSN design/ analysis / implementation.

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Nitika Rai received Bachelor's in Electronics and Telecommunication Engineering (EXTC) from Government Engineering College, Jabalpur (M.P.), India in 1993, Masters in EXTC from Veermata Jijabai Technological Institute (VJTI), Mumbai, India in 2007 and is currently pursuing PhD in the area of Wireless Sensor Networks at VJTI. She is working as Associate Professor in the Department of Information Technology at St. Francis Institute of Technology, Mumbai, India. Her research interests include Wireless Networking, Mobile Communication, Participatory Sensing and Antenna Design.

Rohin Daruwala is Professor & Head, Electrical Engineering Department, at Veermata Jijabai Technological Institute, Mumbai, India. He received his Bachelor of Engineering from Sardar Vallabhbhai National Institute of Technology, Surat, India, Master of Engineering and PhD from Mumbai University, India. He has 30 years of experience in teaching undergraduate and post graduate students. His research interests include Digital Design, Computer architecture, Microprocessor Systems Design, Wireless Networks and Internet of Things.