Probabilistic Coverage in Wireless Sensor Networks

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***Abstract*— The sensing capabilities of networked sensors are affected by environmental factors in real deployment and it is imperative to have practical considerations at the design stage in order to anticipate this sensing behaviour. We investigate the coverage issues in wireless sensor networks based on probabilistic coverage and propose a distributed *Probabilistic Coverage Algorithm (PCA)* to evaluate the degree of confidence in detection probability provided by a randomly deployed sensor network. The probabilistic approach is a deviation from the idealistic assumption of uniform circular disc for sensing coverage used in the binary detection model. Simulation results show that area coverage calculated by using PCA is more accurate than the idealistic binary detection model.**

I. Introduction

Recently Wireless Sensor Networks (WSN) has been a subject of immense research interest in the networking community. A WSN is composed of tiny sensor nodes each capable of sensing some phenomenon, limited data processing and communicating with each other [1]. These tiny sensor nodes are deployed in the target field in large numbers and they collaborate to form an ad-hoc network capable of reporting the phenomenon to a data collection point called sink or base station.

WSN have the potential to influence our daily lives to a great extent and have many potential civil and military applications i.e., they can be utilized for object tracking, intrusion detection, habitat and other environmental monitoring, disaster recovery, hazard and structural monitoring, traffic control, inventory management in factory environment and health related applications etc. [2], [3]. These myriad of applications present various design, operational, and management challenges for wireless sensor networks. The challenges become even more demanding if we consider the constraints of wireless sensor networks such as low processing power and bandwidth, limited battery life, and short radio ranges.

Wireless sensor networks differ from ad-hoc networks in several ways. One of the distinguishing features is the introduction of the sensing component in sensor networks. A node in a sensor network is thus performing two demanding tasks simultaneously, sensing the envoirnment and communicating with each other to transfer useful information.

Sensing is a task of paramount importance for proper functioning of wireless sensor network. The sensing coverage of a sensor node is usually assumed uniform in all directions (represented by unit disc), following the binary detection model. An event that occurs within the sensing radius of a node is always assumed detected with probability 1 while any event outside this circle of influence is assumed not detected. This idealized model has been extensively used in recent research works to predict the total coverage in the target area. However, this model is based on unrealistic assumption of perfect coverage in a circular disc for all the sensors. The sensing capabilities of networked sensors are affected by environmental factors in real deployment and it is imperative to have practical considerations at the design stage in order to anticipate this sensing behaviour.

In this paper, we explore the problem of determining the coverage, provided by non-deterministic deployment of sensors, using a more realistic probabilistic coverage model. To capture the real world sensing characteristics of sensor nodes, we assume that the signal propagation from a target to a sensor node follows a probabilistic model. This assumption is only valid for certain kind of sensors e.g. acoustic, seismic etc. where the signal strength decays with the distance from the source and does not hold true for sensors that only measure local point values e.g. temperature, humidity, light etc. Our work therefore target applications like object tracking and intrusion detection that require a certain degree of confidence in the detection probability. This work is based on the path loss log normal shadowing model [4] although it can be extended to incorporate different signal decay models e.g. acoustic signal model (where signal roughly decays at inverse square of distance) for acoustic sensors. We propose the *Probabilistic Coverage Algorithm (PCA)*, an extension of the perimeter coverage algorithm of [5], to evaluate the maximum supported detection probability for a target area. The proposed algorithm can be used to evaluate the effective coverage that can be provided to the application utilizing the sensor network. Simulation results shows that coverage calculated using probabilistic coverage algorithm is more accurate than the idealistic binary detection model.

The remainder of this paper is organized as follows. We discuss related research work in Section II and introduce the problem area by discussing some technical preliminaries in Section III. Section IV elaborates the probabilistic coverage algorithm. Some simulation results are presented in Section V and Section VI concludes the paper.

II. Related Work

The coverage problem has been interpreted in a variety of ways in existing literature. Coverage has been considered in terms of maximal support and breach paths, exposure, quality of surveillance and area coverage etc. Area coverage checks whether every point in the target area is at least covered by a sensor node such that there is no coverage hole in the target area. Our work is more related to the area coverage and hence we limit the discussion here to related work in area coverage.

For a static sensor network (without mobility support), several topology/density control protocols has been proposed that select a minimal number of on-duty nodes that are active at any time out of the available densely deployed nodes. This node scheduling is feasible as long as no coverage holes appear due to nodes being turned off for energy savings. Protocols assuming single coverage includes [6], [7], [8], [9] etc. while [5], [10], [11] etc. consider multiple coverage requirements. Other research efforts aimed at maximizing coverage at deployment time utilizing mobility of sensors. [12] is a computational geometry based approach, [13] [14] are potential field based approaches and [15] is an incremental deployment scheme. All these protocols assume a sensor network where all nodes are mobility capable while [16], [17], [18] consider a hybrid network where only some of the sensors are mobile.

Most of the aforementioned coverage related protocols assume uniform sensing ranges. Probabilistic coverage for sensor networks has been explored in some research efforts but in different context than our work. [19] proposes an error model targeting a location estimation application assuming probabilistic coverage for sensors. A signal strength based approach is used that model a probabilistic function that depends on the distance between the sensor and the object. The authors proposed a single value, overall weighted error degree, as a metric to evaluate the location tracking capability of a sensor network. [20] give an analytical model based on probabilistic coverage to track a moving object in the sensor field. This approach assume that sensor deployment is dense enough to support duty cycling of nodes to save energy at the cost of providing probabilistic coverage. In [21], the authors propose a grid based clustered approach to evaluate the detection probability. The cluster head is responsible for calculating the probability of detection at grid points. This approach assume all sensors are mobility capable and the cluster head can direct nodes to re-adjust their positions in the topology for gain in detection probability.

Our work is different from these research efforts in several ways. First we propose a computational geometry based approach assuming probabilistic coverage characteristics for the deployed sensor nodes. Second, the coverage is calculated at perimeter of each node sensing circles instead of generalized grid points. This gives us a more accurate coverage calculations for each node. Third, the proposed approach is truly distributed, all nodes run the algorithm as compared to the cluster head performing the coverage calculations as in [21]. This has the added advantage of being scalable and robust to failures e.g. cluster head malfunctioning etc.

Our approach is similar to the perimeter coverage algorithms proposed in [5] in that we also propose perimeter coverage as mean to ascertain area coverage. Two different algorithms, k-NC and k-UC are proposed in [5]. Both these algorithms use the binary detection model. For k-NC, although the sensing range is assumed different in different directions, every location within the sensing range is always assumed covered/detected with probability 1. Our work differ from this approach in that our main assumption is that sensing capabilities in all directions is always probabilistic in nature and that the detection probability depends on the relative position of the event/target from the sensor.

III. Technical Preliminaries

The probability of detection of a target by a sensor decreases exponentially with increase in distance between the target and the sensor. Using the log-normal shadowing model, the path loss PL(in dB) at a distance d is given by Equation 1.

$$\overline{PL(d)} = \overline{PL(d0)} + 10 \cdot n \cdot log(\frac{d}{d0}) + X_\sigma \tag{1}$$

where

$d0$ = Reference distance
n = Path loss component, indicating the rate at which the path loss increases with distance
X_σ = Zero-mean Gaussian distributed random variable (in dB) with σ-variance (shadowing, also in dB)
$\overline{PL(d0)}$ = Mean path loss at reference distance d0.

Equation 1 captures various envoirnmental factors resulting in different received signal values at different locations although the distance between the target and sensor is the same. n and X_σ can be measured experimentally as in [22]. Similarly $PL(d0)$ can be measured experimentally for given event and sensor characteristics or can be calculated using free space path loss model [4].

Each sensor has a *receive threshold* value γ that describes the minimum signal strength that can be correctly decoded at the sensor. The probability that the received signal level at a sensor will be above this receive threshold, γ, is given by Equation 4, requiring Q-function to compute probability involving the Gaussian process. The Q-function is defined as

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

where

$$Q(z) = 1 - Q(-z) \tag{3}$$

$$Pr[Pr(d) > \gamma] = Q[\frac{\gamma - Pr(d)}{\sigma}] \tag{4}$$

For a given transmit power and receive threshold value, we can calculate the probability of receiving a signal above the receive threshold value, γ, at a given distance using Equations 4 and 2.

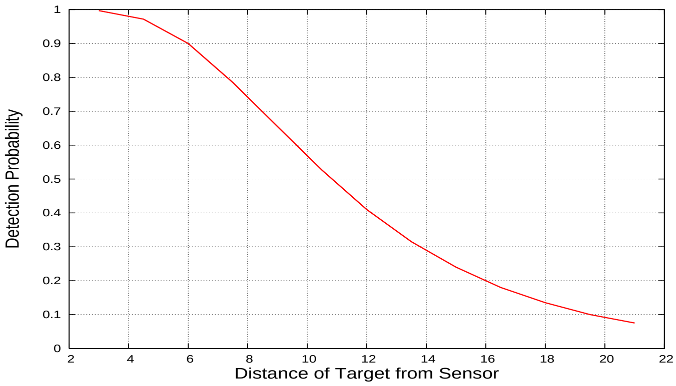

Fig. 1. Change in Detection Probability with Distance(m)

Figure 1 shows the decrease in detection probability for a sensor based on shadowing model for parameters shown in Table I. The change in detection probabilities with distance can be represented by concentric circles drawn at constant distance increment around the sensor location. Each circle thus represent the probability of correctly receiving a signal with strength above receiving threshold at distance equal to radius of the circle.

For a deployed sensor network, a point in the target region can be covered by more than a single sensor. To find the cumulative detection probability at a point in the region, we find the product of the individual detection probabilities of all sensors receiving the event occurring at that point. Thus the overall detection probability Pr of a point in the region is given by (5)

$$Pr = 1 - \prod_{i=1}^{N} (1 - Pr_i) \tag{5}$$

where

N = Number of sensor node covering a particular point

Pr_i = Detection probability of a point for a sensor i

TABLE I

Parameter	*Value*
Transmit power P_t(Target)	24.5 dBm
Receiving threshold (γ) at sensor	-27.85 dBm
Path loss exponent n (free space)	2
σ	4 dBm
Effective coverage range	20m
Communication range	40m
Region (A)	100m x 100m
Number of nodes	60,80,100,120

IV. Probabilistic Coverage Algorithm

The coverage not only depends on the sensing capabilities of the sensor but also on the event characteristics [23] e.g. target detection of military tanks as compared to detection of movement of soldiers depends on the nature and characteristics of event as well as the sensitivity of the sensors involved. We therefore, assume for this work that the transmit power, P_t (characteristic of event) and receive threshold for sensor, γ, is known through experiments and sensor calibration. Once the transmit power and the receive threshold of sensors are known, a *probability table*, PT (see Table II) can be precomputed (using Equations 1 - 4) that provides the detection probability at various distances from the sensor.

TABLE II

A Sample Probability Table (PT)

Distance (m)	*Probability*
3	0.997
6	0.90
9	0.655
12	0.41
15	0.245
18	0.135

Definition 1: Effective coverage range, R_{effec}, of a sensor S_i is defined as distance of the target from the sensor beyond which the detection probability is negligible.

For this work R_{effec} is taken as the distance at which the probability of detection falls below 0.1, the decision to take the value less than 0.1 as negligible will be explained when we cover the actual algorithm.

Following definition 1, two sensors Si and Sj are considered neighbors in region A, contributing to coverage of each other, only if the Eucilidian distance between them, d$_{ij}$, is less than twice the effective coverage range, R_{effec}. Figure 2 shows the cumulative detection probability, for two neighbors in a region, for parameters listed in Table 1. The distance between the two nodes is 24m. If an event occurs at the midpoint between the two sensors Si and Sj, the cumulative detection probability using Equation 5 is 0.65 while the individual detection probabilities for both S_i and S_j is 0.41. If the event is moved toward either of the sensor, the cumulative detection probability is higher than this minimal value at the midpoint. It is obvious that the cumulative detection probability is higher if neighbor sensors are located near each other.

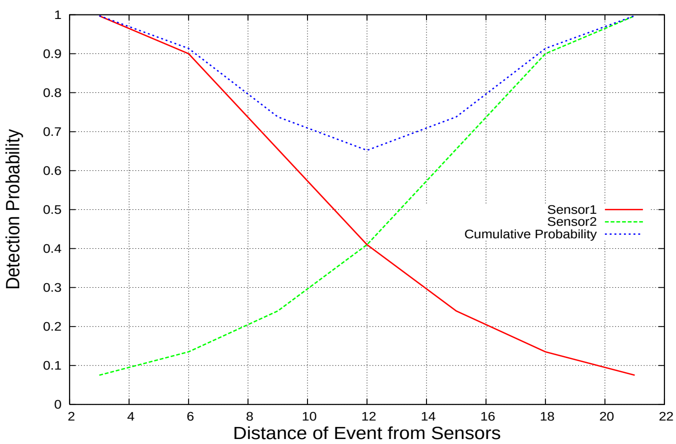

Fig. 2. Detection Probabilities

If ρ_{reqd} represents the desired detection probability (DDP) for a region, a simple approach to calculate the coverage is to apply the perimeter coverage algorithm proposed in [5], assuming the sensing range of all the sensor nodes equal to a distance, d_{reqd}, from the sensor that provides ρ_{reqd}. This is similar to using the binary detection model with sensing range set to d_{reqd} thus restricting neighbor relationship to sensors located within twice the d_{reqd}.

But if we look at Fig 2, we observe that the detection probability at any location is increased by contributions from the sensors covering that point and this cumulative effect is more profound if the sensors are located near each other. It is thus possible to achieve the desired detection probability at distances greater than the d_{reqd} by considering the contribution of neighbor nodes within the effective sensing range. It is obvious that the region bounded by d_{reqd} is covered by ρ_{reqd} but neighbor contributions may make region bounded by distances greater than d_{reqd} covered by detection probability in excess of the required detection probability, ρ_{reqd}. The basic idea is to take the next higher distance from the probability table PT as d_{eval} (with lower detection probability than ρ_{reqd}) and evaluate whether contributions from neighbors makes the perimeter at d_{eval} sufficiently covered or not.

Definition 2: A location in region A is said to be sufficiently covered if its cumulative detection probability, due to sensors located within the effective coverage range R_{effec} of this location, is equal to or greater than DDP, the detection probability desired by the application.

The application utilizing the sensor network thus dictates the desired threshold for coverage probability, ρ_{reqd} and our objective is to check whether all locations in the given region are sufficiently covered or not.

A. The Algorithm

We adopt a computational geometry based approach and propose Probabilistic Coverage Algorithm (PCA) to check whether the currently deployed topology supports the required coverage probability or not. We make the following assumptions for this work.

- Sensors are randomly deployed in the field.
- Location information is available to each sensor node.
- Communication range of sensors is at least twice the effective coverage range, R_{effec}.
- Sensors can detect boundary of the region if the boundary is within a sensor's R_{effec}.
- Transmit power of target P_t and receive threshold γ for a sensor are known and γ is the same for all the sensors.
- Mean values of path loss component n and shadowing deviation σ are assumed for all the sensors.

In the initialization phase of the algorithm, a node Si receives location information from all of its one hop communication neighbors. It calculates the distances to all such neighbors and keep them in a list sorted on distances. Si has two sensing circles with radius d_{reqd} and d_{eval}. d_{reqd} is the distance from the sensor providing ρ_{reqd} while d_{eval} is the next distance increment that is greater than d_{reqd} providing a lower detection probability than ρ_{reqd}. Both d_{reqd} and d_{eval} are taken from the PT.

Node S_i first detects whether it is within vicinity of the region boundary. We assume that a node can detect boundary if it is within distance R_{effec} from the boundary of the region. If the region boundary intersects the circle of S_i at d_{eval}, the node marks points on the perimeter that lies outside the boundary of region. The segments on perimeter that lie outside the region boundary (segment of S_i between $b1$ and $b2$ in Figure 3) are assigned detection probability of 1, implying that the sensor do not need to calculate coverage for this part of the segment as it is out of region boundary.

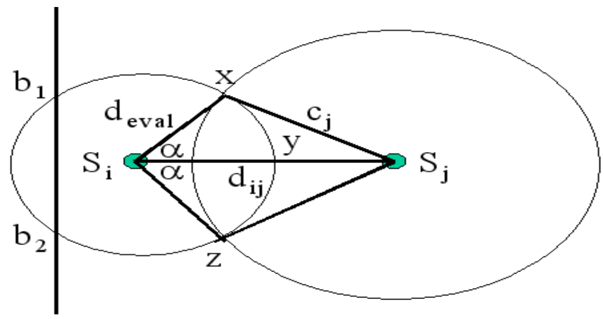

Fig. 3. Neighbor Contribution to Coverage

In the next step, neighbor contributions towards detection probability is calculated. Neighbors that are within a distance of $d_{eval} + R_{effec}$ from S_i are only considered for probability calculations, other nodes do not contribute any coverage to S_i's perimeter at d_{eval}.

A node Sj that is a neighbor of Si has several concentric circles representing regions of different detection probabilities (see Fig 4) . These circles can be evaluated at fixed distance increments or at fixed detection probability decrements from the node. The value of distance increment (or probability decrement) being a tradeoff between the computational time and detection granularity.

Node S_i calculates the cumulative detection probability at intersection of circle at d_{eval} with various circles of neighbor S_j. For an example refer to Fig 3. Node S_i calculates cumulative detection probability using Equation 5 at the point x, the intersection of its circle with radius d_{eval} with its neighbor S_j circle cj. The segment on perimeter that is covered by the circle c_j is calculated using the cosines rule.

$$\cos\alpha = (d_{eval}^2 + d_{ij}^2 - c_j^2)/(2 \cdot d_{eval} \cdot d_{ij}) \qquad (6)$$

where α is the angle subtended by the segment xy on perimeter of S_i. It is easy to prove that coverage on segment yz is similar to that in segment xy as total angle subtended by segment xz is 2α. This calculation is repeated for all the circles of the neighbor S_j that are intersecting S_i circle at d_{eval} (see Figure 4). $C(r, p)$ in Figure 4 represent the circle around S_j with radius r providing probability of detection p.

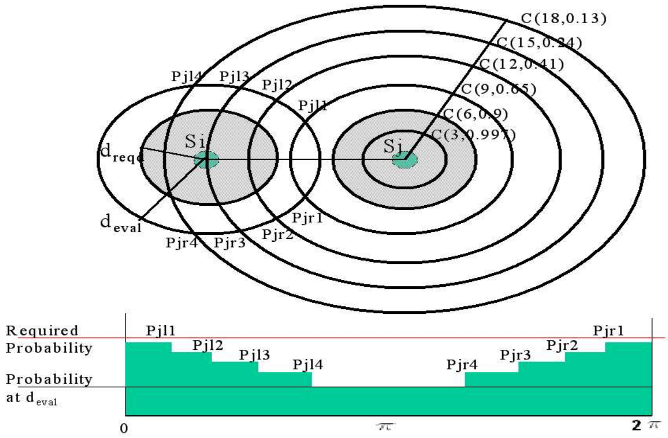

Fig. 4. Perimeter Coverage using PCA

Algorithm 1 Probabilistic Coverage Algorithm (PCA)

Notations :
ρ_{reqd} = Desired detection probability
d_{reqd} = Radius of circle around S_i that provides ρ_{reqd}
ρ_{eval} = Detection probability at next circle with $\rho < \rho_{reqd}$
d_{eval} = Radius of circle around S_i providing ρ_{eval}
ρcum_{ij} = Cumulative detection probability of S_i and S_j
R_{effec} = see Definition 1
$G\alpha$ = Angle subtended by the arc on perimeter of sensor S_i circle with radius d_{eval} that is covered by a neighbor
$G\rho$ = Cumulative probability of detection on perimeter of S_i circle with radius d_{eval}
$C_i(x)$ = Circle of S_i with radius x
Input :
ρ_{reqd}
Neighbor locations
Probability table (PT) of probabilities P and distances D (precomputed)
Process :
1: ascertain ρ_{eval} and d_{eval} from PT
2: check boundary intersection with circle at d_{eval}
3: **if** $C_i(d_{eval})$ lies outside the region boundary **then**
4: mark segments on perimeter of $C_i(d_{eval})$ that are outside the boundary as sufficiently covered
5: **end if**
6: sort the neighbor list in ascending order of distance
7: **for** each neighbor j **do**
8: **if** $d_{ij} < d_{eval} + R_{effec}$ **then**
9: **for** each circle of S_j in D $(C_j(D_j))$ that intersects with $C_i(d_{eval})$ **do**
10: **if** $D_j < d_{eval}$ **then**
11: mark intersection point on perimeter of $C_i(d_{eval})$ as sufficiently covered by ρ_{reqd}
12: **else**
13: mark intersection point on perimeter of $C_i(d_{eval})$ as covered by ρcum_{ij}
14: **end if**
15: **end for**
16: update global $G\alpha$ and $G\rho$
17: sort $G\alpha$ and $G\rho$ in ascending order on $G\alpha$
18: **if** $G\alpha$ is all covered from 0 to 2π with $G\rho \geq \rho_{reqd}$ **then**
19: declare all perimeter at $C_i(d_{eval})$ is sufficiently covered
20: end algorithm
21: **end if**
22: **end if**
23: **end for**
24: declare perimeter at $C_i(d_{eval})$ is not sufficiently covered

The cumulative detection probability is then placed on a line segment $[0, 2\pi]$ representing the perimeter of S_i at d_{eval} (see lower part of Fig 4). This is repeated for each neighbor until whole perimeter is found covered by probability $\rho \geq$ DDP. If this happens, PCA can declare that region around the sensor S_i bounded by circle with radius d_{eval} is *sufficiently covered* otherwise the algorithm declares that required detection probability cannot be provided at d_{eval} and only the region bounded by circle with radius d_{reqd} is sufficiently covered.

The pseudo-code for probabilistic coverage algorithm is listed in Algorithm 1 and some of the optimizations are discussed here.

Line No. 6 in the pseudo-code listing sorts the neighbor list in order of increasing distance. This is to reduce the computational time for the algorithm. As the output of the PCA is a binary decision, covered or not, calculating the coverage starting from the nearest located neighbor onward increases the likelihood of terminating the algorithm earlier in case the perimeter is found covered with neighbor contributions. This is because neighbors located close to the node making the decision influence the perimeter more than those located far away.

The coverage influence check (Line 8) ensures that the algorithm is only run when any probability circle of the neighbor intersects with circle at d_{eval} of node running the PCA.

Lines 10-14 are better explained by looking at the Figure 5. In Figure 5(a), S_i and S_j are located such that S_i circle at d_{eval} is intersecting with S_j circle with radius d_{reqd} at points a and b. We can observe that the perimeter of S_j with radius d_{reqd} is covered with ρ_{reqd} and the segment of S_i between a-b gets cumulative probability greater than ρ_{reqd}. We, thus, do not need to calculate the cumulative detection probability for segments that intersect with neighbor circles with radius less than d_{eval} and such segments can simply be marked as sufficiently covered with ρ_{reqd}. Considering the region bounded by segment $a - b$ in Figure 5(a), we want to check whether the probability of detection in region enclosed by $a, b, candd$ (marked by slashes) is at least ρ_{reqd} or not. We observe that points a, b, c and d are all covered with probability at least ρ_{reqd} and that as we move in the slashed region from

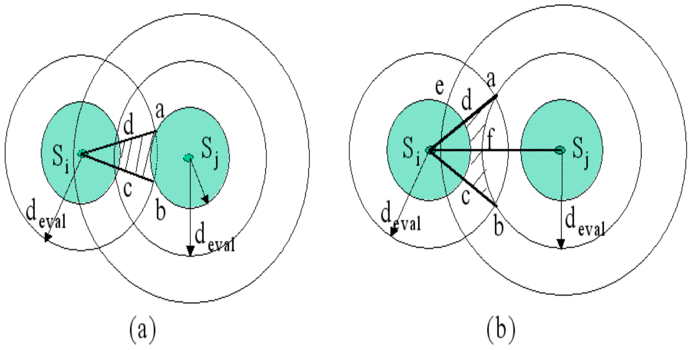

Fig. 5. Coverage calculations

S_j towards S_i, contribution from S_i is increasing while that from S_j is decreasing resulting in slashed region being covered with at least ρ_{reqd}.

Considering the case where the intersecting circle of S_j has radius greater than or equal to d_{eval}, Figure 5(b), the segment between points a-b is marked covered with ρcum_{ij}, cumulative detection probability. Also segment of S_i between c-d is covered with probability greater than ρ_{reqd}. The probability inside the slashed region thus increases as we move from segment a-b towards segment c-d. To make sure this increase is always there, we select the R_{effec} as distance from sensor at which the detection probability falls below 0.1. This ensures that the enclosed region (slashed) always has contributions from the neighbor even when the neighbor max radius circle (R_{effec}) is being considered as intersecting with S_i circle. This leads to the following definition.

Definition 3: If the perimeter of a sensor Si circle with radius d_{eval} is covered by cumulative detection probability ρ_{reqd}, the region inside the circle is sufficiently covered with detection probability at least ρ_{reqd}.

Finally, line 18 in pseudo-code listing is an early termination check. The algorithm checks whether the desired detection probability has been achieved after calculating the influence of coverage of each neighbor and if so, the result is declared as $C_i(d_{eval})$ sufficiently covered and the algorithm terminates.

Theorem 1: The whole region A is sufficiently covered by ρ_{reqd} if all sensors in the region has perimeter, of circle with radius d_{eval}, sufficiently covered with detection probability $\rho \geq$ DDP.

PROOF: Each sub-region inside the region A is bounded by at least one segment of a sensor perimeter with circle with radius d_{eval}. Following definition 3, if perimeter of a sensor at d_{eval} is sufficiently covered, inside sub-region bounded by circle $C(d_{eval})$ is sufficiently covered. Also observe that the perimeter of $C(d_{eval})$ can only be sufficiently covered if a neighbor has contributed to its coverage or segment of its perimeter lies outside the region boundary. The whole region is thus sufficiently covered only if all the sensors located in the region has their perimeters as sufficiently covered.

Each sensor calculate this perimeter coverage independently and can report whether the region bounded by its circle with radius d_{eval} is sufficiently covered or not. Following Theorem 1, if all the sensors report sufficiently covered perimeters at $C_i(d_{eval})$, the whole region is sufficiently covered. If a sensor finds its perimeter is not sufficiently covered, it has identified a coverage hole in the region, an area that is not sufficiently covered to the required detection probability. The information from all sensors describe the current state of area coverage supported by the sensor network. In case of coverage hole detection, this information can be utilized to deploy more sensors in the topology or to guide mobility capable redundant nodes to specific locations to satisfy the detection probability constraint.

B. Extension

The probabilistic coverage algorithm gives a binary decision, a yes/no, whether the region is covered with the required detection probability or not. This is accomplished by distributed decision making at each sensor node. The basic PCA can be easily extended to not only identify the presence of coverage holes in the region but also to suggest possible deployment points in the region to cover those coverage holes. An uncovered perimeter at circle with radius d_{eval} indicates a coverage hole. This information is readily available after executing the PCA.

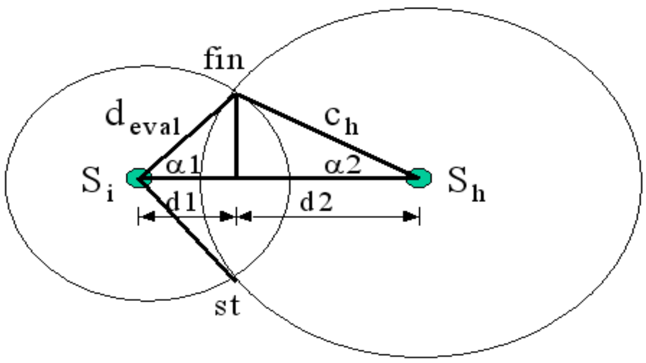

Fig. 6. Identifying deployment point

Refer to Fig 6, st and fin are the start and end points of the maximum uncovered segment (having detection probability $< \rho_{reqd}$) on perimeter of S_i's circle with radius d_{eval}. There can be a number of uncovered segments in the perimeter but the one with lowest existing detection probability is selected. The task is to determine the deployment location where a redundant helper node, S_h, can be placed such that the perimeter coverage constraint for the current node is satisfied. Let ρ_{exist} represent the existing detection probability in the uncovered segment ($\rho_{exist} < \rho_{reqd}$), we need to calculate ρ_{help}, the probability required out of helping node that can enhance ρ_{exist} to at least ρ_{reqd}.

$$\rho_{help} = 1 - \frac{(1 - \rho_{reqd})}{(1 - \rho_{exist})} \quad (7)$$

ρ_{help}, given by Equation 7, is used to index the probability table, PT, to select appropriate distance C_h (radius of S_h), that gives $\rho \geq \rho_{help}$. We refer to probability at this distance as ρ_{select}.

Fig 6 illustrates how to calculate the coordinates for helper node S_h once C_h has been selected. Required information for deployment location is the orientation and distance of deployment point from the current node. The required orientation , α_{dep}, is given by $st + \frac{(fin-st)}{2}$. Distance from the current node is divided into $d1$ and $d2$ (see Fig 6). $d1$ is calculated using Equation 8.

$$d1 = \frac{d_{eval} \cdot \sin(\alpha 1)}{\tan(\alpha 1)} \quad (8)$$

For distance $d2$, an additional check is made whether C_h, the circle that provide ρ_{select}, can completely cover the uncovered segment between st and fin. If C_h cannot completely cover the segment, we have to place S_h at perimeter of S_i (total distance from S_i is d_{eval}) to ensure maximum possible coverage gain. Thus if $d_{eval} \cdot \sin(\alpha 1) > \rho_{select}$ take $d2 = (d_{eval} - d1)$ otherwise use Equations 9 and 10 to calculate $d2$.

$$\alpha 2 = \sin^{-1}\left(\frac{d_{eval} \cdot \sin(\alpha 1)}{\rho_{select}}\right) \quad (9)$$

$$d2 = \frac{d_{eval} \cdot \sin(\alpha 1)}{\tan(\alpha 2)} \quad (10)$$

The orientation of the required deployment is known (α_{dep}) and the distance from the node is given by $d1 + d2$. This information can easily be resolved into the coordinates for deployment. The sensor can advertise this location for help or can bid for nearby mobile sensor nodes similar to that in [18].

V. SIMULATION SETUP

The probabilistic coverage algorithm has been implemented in Ns2 simulator. Simulation setup parameters are listed in Table 1. Figure 7 shows the number of nodes reporting sufficiently covered perimeters for PCA and binary detection model with circular disc with radius d_{reqd}. d_{reqd} is 6m for ρ_{reqd} 0.9 while d_{eval} is 9m providing ρ_{eval} 0.655.

With 60 nodes in 100 x 100 m region, PCA reports perimeter coverage at 9m circle for 11 nodes while binary detection model has only 1 node with whole perimeter covered with required probability of 0.9. At higher node density of 120 the corresponding values are 47 for PCA and 12 for binary detection model. The results are for three different randomly generated topologies for each different number of nodes.

It is clear that the binary detection model (with radius = d_{reqd}) underestimates the total coverage. It will require deployment of more nodes than that are actually required (by PCA) to satisfy the coverage constraint. It also follows that if we select the radius of disc in binary detection model as the effective sensing range, the coverage will be overestimated. The PCA thus provides a more granular and accurate estimate of the coverage and detection probability.

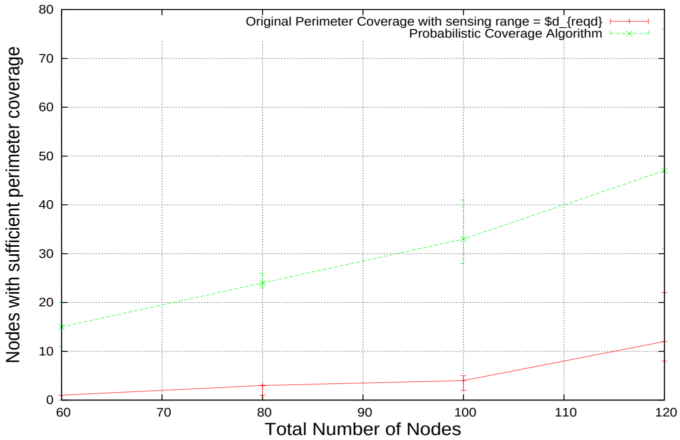

Fig. 7. Simulation Results

VI. CONCLUSION AND FUTURE WORK

We have proposed a probabilistic coverage algorithm to evaluate area coverage in a randomly deployed wireless sensor network. The proposed algorithm takes into account the variations in sensing behaviour of deployed sensors and adopts a probabilistic approach in contrast to widely used idealistic unit disk model. Simulation results reflects the effectiveness of the proposed algorithm in predicting the degree of confidence in detection probability supported by a given deployment.

We have made a number of assumptions in our work and we plan to explore relaxing some of the simplistic assumptions in our future work. e.g., we have assumed mean values of path loss component, n , and the shadowing deviation, σ, for all the sensors in the region. In real deployment scenarios n and σ varies spatially as well as temporally due to changing envoirnments. The consideration of different n and σ for different sub-regions in the sensor network will capture a more realistic sensing behaviour. Similarly our current work assumes an obstacles free region and this is another aspect that needs to be addressed. Finally we plan to incorporate the multiple coverage constraint in our future work. This is useful for many applications for fault tolerance and triangulation based localization etc. The multiple probabilistic coverage constraint can thus be specified as (ρ_{reqd}, k), where k is the degree of coverage.

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