Sensor Distribution on Coverage in Sensor Networks

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Abstract. In this paper, we study the impacts of sensor node distributions on network coverage. We first show the impacts on network coverage by adopting different sensor node distributions through both analytical and simulation studies. Then, we adopt a distribution-free approach to study network coverage, in which no assumption of probability distribution of sensor node locations is needed. The proposed approach has yielded good estimations of network coverage.

Keywords: Coverage, sensor network, distribution.

1 Introduction

In most previous work concerning network coverage problems where sensors are deployed randomly, researchers assume the spatial distributions of sensor nodes are known when evaluating their proposed algorithms or protocols. Major disadvantages of such an analysis method include: 1) it is very difficult to choose an accurate sensor location distribution; 2) inaccurate distribution assumption will result in poor analysis of protocols or algorithms; and 3) changes in sensor distributions may lead to variations in system performance sometimes even invalidate the whole analysis.

Motivated by this intuition, we propose a network coverage analysis approach in which no assumption on sensor location distribution is required. Thus, the approach is in effect a distribution-free approach. The approach is suitable to solve network coverage problem concerning a great number of sensors, which are deployed randomly.

We summarize the contribution of the paper as follows, 1) we evaluated the effects of sensor location distribution via both analytical modeling and computer simulations, and have concluded that accurate sensor location distribution is important to assessment of sensor networks where a great number of sensors are randomly deployed; 2) we then propose a distribution-free sensor network modeling approach, which uses a non-parametric statistical approach; 3) we verify the approach by using our previous work in [10] as an example.

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2 Related Work

A sensor network may contain a large number of simple sensor nodes. Sensor nodes are often powered by batteries, and hence have to operate on limited energy budgets. Furthermore, it is difficult to replace batteries in the sensors deployed in inaccessible or inhospitable environments. Thus, many research efforts have been spent on the energy conservation of sensor nodes to extend sensor network life time [13]. The network lifetime is defined as the time between the initialization of the network and the first case of battery exhaustion among sensor nodes. Extending the network lifetime has been extensively researched [1-3]. A lot of protocols keep a subset of sensor nodes vigilant for sensing and communication tasks while putting the others in power-save mode [4]. On the other hand, energy efficiency should not be achieved at the cost of reduced network coverage and connectivity. Thus, the network coverage and connectivity have also been considered simultaneously in some researches [5-8]. There are many related papers in sensor networks [21-109].

In [9], the authors studied a network with sensor nodes deployed strictly in grids. Plenty of work focus on sensor networks where sensor locations follow a Poisson point process and sensors are uniformly distributed in sensing fields, e.g., [19] and [20]. In [18], barrier coverage problems are studied when sensors are distributed along the line with random offsets due to wind and other environmental factors. In [8], the authors investigate energy efficiency in more general sensor networks where the sensor nodes are deployed randomly. In [10], the authors study a randomized scheduling algorithm where sensors are uniformly distributed. The paper [14] proposes a worst and average case algorithm for coverage calculation from a perspective of computational geometry where no sensor location distribution is required. Nevertheless, little work has been done where no prior knowledge of sensor node location distribution is required.

This paper studies the impact of sensor location distributions on network coverage and provides a distribution-free approach in which no assumption on sensor location distribution is required and sensor locations can be in any distribution. To the best of our knowledge, no literature is found to apply distribution-free approach to sensor network coverage problems.

3 Coverage Intensity

3.1 Coverage Intensity

Assume n sensors are randomly deployed to form a wireless sensor network to cover a field, which we refer to as the sensing field. The sensor network runs a randomized scheduling algorithm. The randomized scheduling algorithm is given as follows. Let S denote the set of all the n sensor nodes. Let S be divided into k disjoint subsets S_j $(j = 1, 2, ..., k)$ and each sensor node is randomly assigned to one of these subsets. At any time, only one subset of sensor nodes are active and the rest of sensor nodes are inactive. The objective is to extend the network life time and maintain satisfactory coverage. We measure the coverage using coverage intensity.

Network coverage intensity is the ratio of the time when a point in the field of the sensor network is covered by at least one active sensor node to the total time. We model the sensor node deployment field as a two-dimensional Cartesian coordination system. The field ranges from *0* to *X* and *0* to *Y* on X- and Y-axis respectively. Assume that the sensing area of a sensor is the area of a circle and the sensing range of sensors is *R*, the radius of the circle. Let $f(x, y)$ denote the probability density function of sensor node locations. Actual deployment of sensor nodes may be unknown, and $f(x, y)$ can be any distribution. Let $P(g, h)$ denote the probability that a given point (g, h) is covered by at least one sensor node. We have

$$P(g,h) = \iint_{(x-g)^2+(y-h)^2 \le R^2} f(x, y)dxdy \tag{1}$$

Since *n* sensors are divided into *k* disjoint subsets, which take turns to wake up and perform sensing tasks while the rest of the subsets are in power-save mode. Then the probability that point (g, h) is covered by an active sensor can be written as

$$C(g,h) = 1 - [1 - P(g,h)/k]^n \tag{2}$$

Coverage intensity is the detection metrics for the whole network. Note that point (g, h) is randomly chosen from the sensing field. Thus, the network coverage intensity for the network is

$$C_n = E(C(g,h)) \tag{3}$$

It is worth noting that in the above discussion, no assumption on sensor location distribution is given, and the sensor location distribution can be any distribution, which can even be a distribution which has no explicit form.

The above derivation does not consider edge effect. Since the whole sensing field must have boundaries, a coverage area of a sensor node may not be completely inside the whole sensing field, which we refer to as the edge effect. The computer simulations in Section V show that the error rate between the simulation and analytical results is very small and can be neglected when the number of sensors is large.

3.2 Uniform Distribution

Assume that sensors are uniformly deployed in the sensing field. This case is studied in detail in [10]. For comparison purpose, we reformulate the coverage intensity using the result obtained in previous subsection. Sensor location (g, h) follows a two-dimensional uniform distribution, namely $f(x, y) = 1/(XY)$. Plug this into equations (1)-(3), we can obtain the network coverage intensity for the two dimensional uniform distribution.

$$P^U(g,h) = \iint_{(x-g)^2+(y-h)^2 \le R^2} \frac{1}{XY} dxdy = \frac{\pi R^2}{XY} \tag{4}$$

$$C^U(g,h) = 1 - [1 - \frac{\pi R^2}{kXY}]^n \tag{5}$$

$$\begin{aligned} C_n^U &= E(C(g,h)) = \int_0^Y \int_0^X \frac{1}{XY} \left\{ 1 - [1 - \frac{\pi R^2}{kXY}]^n \right\} dxdy \\ &= 1 - [1 - \frac{\pi R^2}{kXY}]^n \end{aligned} \tag{6}$$

where we use superscript U to indicate that sensor locations follow a two-dimensional uniform distribution.

3.3 Two-Dimensional Gaussian Distribution

Assume that sensor nodes deployed in the sensing field follow a two-dimensional Gaussian distribution. The probability density function of the two-dimensional Gaussian distribution is given as

$$f(x,y) = \frac{1}{2\pi\sigma^2} e^{-[(x-X/2)^2 + (y-Y/2)^2]/2\sigma^2}$$

Plugging this into (1), we have

$$P^G(g,h) = \iint_{(x-g)^2+(y-h)^2 \le R^2} \frac{1}{2\pi\sigma^2} e^{-[(x-X/2)^2 + (y-Y/2)^2]/2\sigma^2} dxdy$$

where subscript G indicates that sensor locations follow a two-dimensional Gaussian distribution.

Let $x' = x - g$ and $y' = y - h$,

$$P^G(g,h) = \iint_{x'^2+y'^2 \le R^2} \frac{1}{2\pi\sigma^2} e^{-[(x'+g-X/2)^2 + (y'+h-Y/2)^2]/2\sigma^2} dx'dy'$$

Let $x' = l\sin\theta$, $y' = l\cos\theta$, and $|J| = |\frac{\partial(x',y')}{\partial(l,\theta)}| = l$,

$$\begin{aligned} P^G(g,h) &= \int_0^R \int_0^{2\pi} \frac{1}{2\pi\sigma^2} e^{-[(l\sin\theta+g-X/2)^2 + (l\cos\theta+h-Y/2)^2]/2\sigma^2} |J| dld\theta \\ &= \int_0^R \int_0^{2\pi} \frac{1}{2\pi\sigma^2} e^{-[(l\sin\theta+g-X/2)^2 + (l\cos\theta+h-Y/2)^2]/2\sigma^2} ldld\theta \end{aligned} \tag{7}$$

Plug (8) into (2) and (3), we have,

$$C^G(g,h) = 1 - [1 - P^G(g,h)/k]^n \tag{8}$$

$$C_n^G = E(C^G(g,h)) \tag{9}$$

3.4 GU Distribution

In this part, we assume that known sensors location distribution is the one along the x-axis, where sensor locations follow a Gaussian distribution with a mean of $X/2$, and along the y-axis, where sensor locations follow a uniform distribution with a mean of $Y/2$. For simplicity, we name this two-dimensional distribution as a GU distribution. Similar to the above, we need to calculate the probability $P(g,h)$ to obtain coverage intensity under a GU distribution. Thus, we have

$$P^{GU}(g,h) = \iint_{(x-g)^2+(y-h)^2 \le R^2} f(x)f(y)dxdy$$

where $f(x) = \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{(x-X/2)^2}{2\sigma_x^2}}$ and $f(y) = \frac{1}{Y}$. Note that superscript GU indicates that sensor locations follow a GU distribution.

Following the similar steps in previous subsection, we have

$$P^{GU}(g,h) = \int_0^R \int_0^{2\pi} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{(l\sin\theta+g-X/2)^2}{2\sigma_x^2}} \frac{1}{Y} l dl d\theta \tag{10}$$

$$C^{GU}(g,h) = 1 - [1 - P^{GU}(g,h)/k]^n \tag{11}$$

$$C_n^{GU} = E(C^{GU}(g,h)) \tag{12}$$

4 Distribution-Free Approach

In this section, we introduce the distribution-free approach for estimating coverage intensity. The approach uses a non-parametric statistical method [11], [16]. It does not require that the sensor location distribution to be known. Instead, it requires the locations of a few sensors among the deployed sensors.

There are many studies regarding sensor node localization. Common localization approaches rely on a few sensor anchor or beacon nodes whose locations are known in advance, for example, via GPS signals. Thus, we can have a few sensors whose locations can be accurately determined. Due to random factors in real world, such as wind, sensor location distributions are impossible to be exactly the same as assumed distributions. Since inaccurate knowledge on sensor location distributions can yield misleading or invalid network coverage estimations, we propose a distribution-free approach to estimate network coverage intensity. The approach is not based on an assumed distribution. Instead, it is based on the locations of a sample of sensor nodes whose locations are known.

In the rest of this section, we first present how we infer sensor location distribution from the locations of a sample of sensor nodes using a non-parametric statistical method, called Kernel-density estimation [11], [16]. Next, we describe the distribution-free method.

4.1 Infer Sensor Location Distribution from Locations of Sample Sensor Nodes

Denote the locations of randomly selected sample nodes as (X_i, Y_i), $i = 1, 2, \ldots, N$, where N is the sample size. The probability density at any point (x, y) can be estimated using the locations of the sample of sensor nodes, i.e.,

$$\hat{f}_h(x,y) = \frac{1}{Nh_x h_y}\sum_{i=1}^{N} K\left(\frac{x - X_i}{h_x}, \frac{y - Y_i}{h_y}\right) \tag{13}$$

where $K(\cdot)$ is some kernel, and h_x and h_y are smoothing factors or window-width. It is quite often that $K(\cdot)$ is taken to be a standard Gaussian function with mean 0 and variance 1, i.e.,

$$K(u,v) = \frac{1}{2\pi} e^{-\frac{1}{2}(u^2+v^2)} \tag{14}$$

Plugging (14) into (13), we get,

$$\begin{aligned}\hat{f}_h(x,y) &= \frac{1}{Nh_x h_y}\sum_{i=1}^{N} K\left(\frac{x - X_i}{h_x}, \frac{y - Y_i}{h_y}\right) \\ &= \frac{1}{Nh_x h_y}\sum_{i=1}^{N} \frac{1}{2\pi} e^{-\frac{1}{2}\left(\frac{(x-X_i)^2}{h_x^2}+\frac{(y-Y_i)^2}{h_y^2}\right)}\end{aligned} \tag{15}$$

Note that 1) window-width h_x and h_y indirectly control the variance of the Gaussian function, and 2) probability density functions to be estimated can be multi-modal [16] and by no means have to be Gaussian even though the kernel is a Gaussian function.

Choices of N, h, and $K(\cdot)$ are the factors determining the efficiency and effectiveness of the estimation of the probability density.

4.2 Distribution-Free Coverage Intensity Estimation

The approach has four steps, 1) obtaining the locations of the sample sensor nodes; 2) analyzing the locations and obtaining the window-width (h_x and h_y); 3) approximating sensor location distribution using Kernel-density estimation; 4) based on the Kernel-density estimation, calculating the coverage intensity.

Though N and $K(\square)$ are also factors related to the efficiency and effectiveness of the approach, they are determined empirically before sensor deployment in this paper. The above four steps are carried out after sensor deployment without using any assumed sensor location distribution.

The coverage intensity is calculated as follows. Replacing $f(x,y)$ in (1) by (13), we get,

$$\begin{aligned} P^{DF}(g,h) &= \iint_{(x-g)^2+(y-h)^2\le R^2} \hat{f}_h(x,y)dxdy \\ &= \iint_{(x-g)^2+(y-h)^2\le R^2} \frac{1}{Nh_xh_y}\sum_{i=1}^{N} K\left(\frac{x-X_i}{h_x},\frac{y-Y_i}{h_y}\right)dxdy \end{aligned} \quad (16)$$

where superscript *DF* indicates we are using the distribution-free approach. Plugging (16) into (2) and (3), we have,

$$C^{DF}(g,h) = 1-[1-P^{DF}(g,h)/k]^n \quad (17)$$

$$C_n^{DF} = E(C^{DF}(g,h)) \quad (18)$$

5 Simulation Verification

In this section, we perform computer simulations to verify our analytical model presented in Section III. We developed a discrete event simulation program in C++. In our program, there are scheduling events, intrusion starting events, and intrusion departure events. The program is capable of loading any sensor deployment configuration. In our simulations below, sensor nodes are deployed randomly in the sensing field. The purposes of this section are 1) to demonstrate that the analytical model in Section III is accurate; 2) the edge effect is neglectable. For coping with limited space, we show only the results for GU distributions for the first purpose. For the second purpose, we show only the results for the two-dimensional uniform distributions.

In this section, the standard deviation (σ_x) of Gaussian distribution along the x-axis is *20*, the number of deployed sensor nodes (n) is *1000*, the size of the whole sensing field is *10000*, the sensing area of each sensor is 30, and the number of subsets is 4, unless otherwise stated.

Fig. 1 shows the network coverage intensity *vs*. the number of sensor nodes with both analytical and simulation results. The figure shows that the analytical results match exactly with the simulation results. In addition, the network coverage intensity increases as the number of sensor nodes increases, and when the number of disjointed subsets (k) increases, the network coverage intensity becomes smaller.

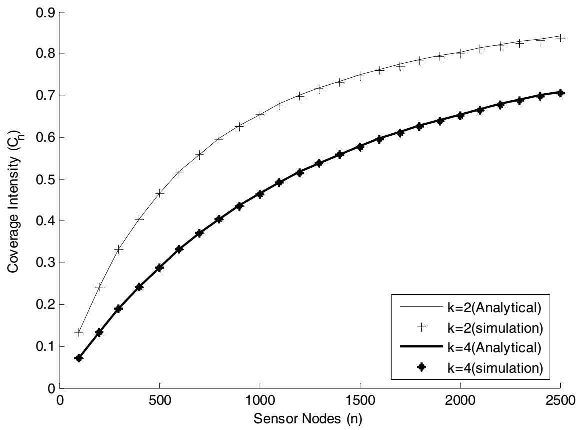

Fig. 1. Coverage Intensity *vs.* n

6 Impacts of Sensor Location Distribution on Network Coverage Estimation

In this section, we show the impacts of inaccurate sensor location distribution on network coverage estimation. Intuitively, the discrepancy between actual and estimated network coverage would occur when the knowledge of the sensor location distribution is inaccurate. We intend to demonstrate that the discrepancy is so great that the inaccurate sensor location distributions may in effect render the network coverage estimation worthless and misleading. This section is organized as follows. 1) We compare the calculated coverage intensity when sensor locations follow two-dimensional uniform and two-dimensional Gaussian distributions respectively. This case can be interpreted as that actual sensor location distribution is a two-dimensional Gaussian distribution; however, we assume the distribution is a two-dimensional uniform distribution; or vice versa. 2) Similarly, we next compare the calculated coverage intensity between two-dimensional uniform and GU distributions.

The coverage intensity for uniform distributions is calculated using equation (6), that for two-dimensional Gaussian distributions using equation (9), and that for GU distributions using equation (12). We choose $X = 100$, $Y = 100$, and $R = 3$ unless otherwise stated.

6.1 Two-Dimensional Gaussian and Uniform Distributions

Fig. 2 shows the coverage intensity *vs.* the number of sensor nodes (n) for both two-dimensional Gaussian distributions and Uniform distributions.

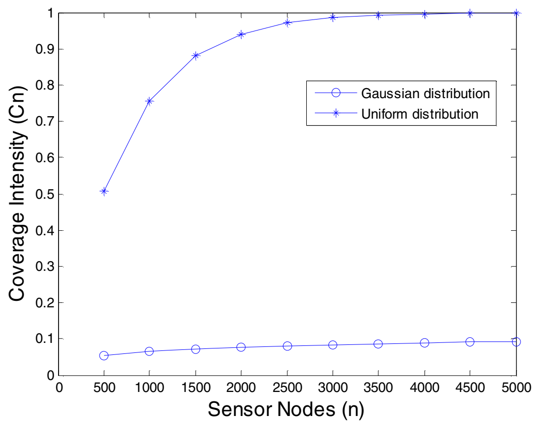

Fig. 2. C_n *vs.* n ($k = 2, \sigma = 5$)

7 Example and Evaluation of Distribution-Free

In this section, we are to demonstrate how to apply the distribution-free approach to estimate network coverage intensity. As discussed in Section IV, three factors affect the effectiveness and efficiency of the approach. The three factors are kernel $K(\square)$, sample size N, and windows-width h_x and h_y. Literature has shown that Gaussian function is a good choice to estimate probability density for continuous random variables using Kernel-density estimation method [16]. Note that probability density functions to be estimated can be multi-modal and by no means have to be Gaussian even though the kernel is a Gaussian function. Nevertheless, we have to determine sample size and windows-width beforehand. In subsection VII.A, we present some discussion on the sample size and the window-width. In subsection VII.B, we present a complete example of the distribution-free approach, and compare the result obtained from the distribution-free approach with that obtained from actual distribution.

7.1 Sample Size

Larger number of sample sensor nodes lead to better estimation of network coverage. Large sample can be obtained by deploying large number of anchor or beacon sensor nodes, or determining accurate locations of large number of sensor nodes, which is either expensive or difficult to achieve. However, when too few sample sensor nodes are chosen, the network coverage estimation can be inaccurate. In this paper, we use a simple method to determine the sample size. The method requires a few number of field experiments,

1. Deploy n sensors in a sensing field via a desirable vehicle, e.g., an aircraft or a rocket. Obtain the locations of all the sensors. The sensors are treated as a population, and we calculated the mean and the variance of the locations of the sensors. Denote the population mean and the population variance as $\overline{Y}$ and S^2 respectively.

2. Randomly select a small number of sensors. The sensors constitute a sample. Obtain their locations. Calculate the mean and the variance of the locations. Denote the sample mean and the sample variance as $\bar{y}$ and s^2 respectively.
3. Calculate the error between the sample mean and the population mean, and denote it as $r = \left(\bar{y} - \bar{Y}\right)/\bar{Y}$.
4. As suggested in [12], the proper sample size is estimated as $n = n_0/\left(1 + n_0/N\right)$ where $n_0 = \left[\left(u_{\alpha/2}S\right)/\left(r\bar{Y}\right)\right]^2$ and $u_{\alpha/2}$ is the value of the vertical boundary for the area of $\alpha/2$ in the right tail of the standard normal distribution.

Repeat the above steps for a few times to converge to the desired sample size.

7.2 Example and Evaluation of Distribution-Free Approach

Step 1:Obtain Locations of Sample Sensors

Before the sensor node deployment, according to the number of sensor nodes deployed in sensor network, we decide the number of sample sensor nodes, and randomly select the sample sensor nodes and equip them with proper components such as GPS receivers to become anchor or beacon nodes. Second, after random deployment, the locations of the sample sensor nodes are obtained via a sensor localization protocol. The locations of the sample sensors are (X_i, Y_i), $i = 1, 2, \ldots N$, where N is the sample size.

Step 2:Window-Width (h)

Many numerical methods have been developed to find *h*, and they mostly minimize the so-called Mean Integrated Squared Error [16]. In our experiment, we use a fast and accurate bivariate kernel density estimator as in [16] to obtain the values of window-width (h_x and h_y). For example, we obtain the bivariate window-width as $(h_x, h_y) = (3.88, 16.71)$.

Step 3:Distribution Estimation

Based on the sample location coordinates from step 1 and bivariate window-width from step 2, the density function can be calculated using equation (15) since we use Gaussian function as the kernel.

Step 4: System Performance Evaluation

In this step, we can use the estimated density function to calculate the network coverage intensity using equations (16)-(18). Fig. 3 shows the estimation results.

Fig. 3 shows the network coverage intensity *vs.* the number of sensor nodes for Uniform distribution, GU distribution and the Estimated GU distribution, where the standard deviation of Gaussian distribution along the x-axis is *5* and the number of

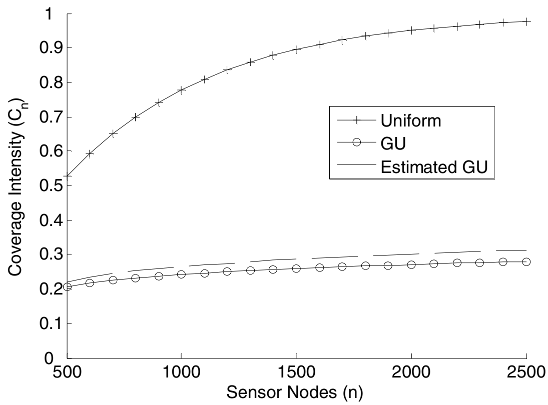

Fig. 3. Estimation performance (size of sample=50)

disjointed subsets is *2*. In the experiment, the size of the whole sensing field is *10000*; the sensing area of each sensor is 30. In Fig.3, in sensor network, the number of whole deployed sensors varies from *500* to *2500*, but we only use *50* sample sensors to estimate the distribution through the kernel density estimation method.

8 Conclusion

Network coverage problems are important to wireless sensor networks. Previous works are based on assumed probability density functions that govern the distribution of sensor nodes in the sensing field. However, the actual distribution of sensor nodes may be very different from the assumed one. Our analytical and simulation studies show that when a different assumption is used, the introduced error on the network coverage metrics can be very large and cannot be neglected.

In this paper, we first reformulate the network coverage intensity using general probability distribution. In other words, we do not assume that the sensor location distributions are known. We verified the formulization using computer simulations, which show that the analytical results and computer simulations match exactly.

Most importantly, we proposed a distribution-free approach for estimating network coverage intensity. In our proposed method, no assumption on sensor location distribution is required. Instead, we take a small sample of the actual deployment, and carry on a statistical analysis to capture the distribution function of the deployment. In practice, this small set of sample can be the sensor nodes equipped with GPS receivers, and thus their locations are known. Furthermore, we used the kernel density estimator to estimate the deployment distribution. Based on the obtained knowledge, the network coverage metrics can be calculated.

The results show that a small sample of sensor nodes yields fairly good estimates on the distribution used. In particular, compared with the case that a different assumption (the uniform distribution) than actual sensor location distribution (GU distribution) is used, the distribution-free approach yields far better results.

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