무선 센서 네트워크에서 Probabilistic Blanket Coverage에 대한 센싱 모델의 영향

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Impact of Sensing Models on Probabilistic Blanket Coverage in Wireless Sensor Network

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요 약

WSN에서의 커버리지 문제는 센싱 커버리지에 대한 요구조건을 만족시키기 위해 필요한 최소한의 활동 센서(active sensor)의 개수로 공식화될 수 있다. 일반적으로 확률적 기하학을 이용하여 WSN의 커버리지 분석을 수행하기 때문에 센싱 모델이 커버리지 분석의 핵심 요소로 간주된다. 따라서, 커버리지 분석의 정확도는 어떠한 센싱 모델을 가정하였느냐에 따라 달라질 수 있으며 분석에 사용된 센싱 모델이 얼마나 실 센싱 환경에 가깝게 특성화 되었느냐에 따라 달라진다. 본 논문에서는 Boolean 모델, Exponential 모델, Hybrid 모델 등 다양한 형태의 결정적 혹은 확률적 센싱 모델들을 조사하고 각각의 센싱 모델에 따라 일정 영역을 센싱할 수 있는 최소한의 센서 개수를 도출할 수 있는 수리적 분석을 수행하였으며 이를 통해 성능을 비교 평가하였다.

Key Words : Blanket coverage, coverage analysis, hybrid sensing model, wireless sensor network

ABSTRACT

In Wireless Sensor Networks (WSNs), blanket (area) coverage analysis is generally carried to find the minimum number of active sensor nodes required to cover a monitoring interest area with the desired fractional coverage-threshold. Normally, the coverage analysis is performed using the stochastic geometry as a tool. The major component of such coverage analysis is the assumed sensing model. Hence, the accuracy of such analysis depends on the underlying assumption of the sensing model: how well the assumed sensing model characterizes the real sensing phenomenon. In this paper, we review the coverage analysis for different deterministic and probabilistic sensing models like Boolean and Shadow-fading model; and extend the analysis for Exponential and hybrid Boolean-Exponential model. From the analytical performance comparison, we demonstrate the redundancy (in terms of number of sensors) that could be resulted due to the coverage analysis based on the detection capability mal-characterizing sensing models.

Ⅰ. Introduction

Typical WSNs consist of densely populated sensor nodes, deployed either deterministically according to some pre-determined pattern or randomly, over a geographical region of interest.

※ 본 연구는 2009년도 정부(교육과학기술부)의 재원으로 한국연구재단의 지원을 받아 수행된 기초연구사업임(No. 2009-0075016).
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논문번호 : KICS2009-09-423, 접수일자 : 2009년 9월 22일, 최종논문접수일자 : 2010년 6월 18일

The general purpose of such WSNs is to sense, collect and report any relevant events/data from the region of interest to the desired destination (or sink). To collect and report the events, every location in the considered region of interest should be within the sensing coverage of at least one connected sensor node. Generally, in randomly deployed WSN, more sensor nodes than the actual requirement are deployed to perform the applications of interest. The redundant sensor nodes are deployed intuitively to compensate the lack of exact position information, and to improve the fault tolerance. However, these redundant sensor nodes, are the cause of energy wastage and the network lifetime minimization [1]. Such energy inefficiency can not be compensated at any cost in energy constrained WSNs. Hence, to prolong the network life time which could have been reduced because of redundancy in number of sensor nodes, a trivial solution that can be applied straightforwardly is density control. It is a simple approach to deactivate the redundant sensor nodes without any coverage and connectivity penalty. For the design of such density control algorithms, information about the minimum set of sensor nodes that can cover the whole or a fraction of monitoring interest area (for the applications like data gathering with allowed fixed delay as in [8] and moving target detection as in [9] certain desired fractional coverage is enough) is required. Such information can be obtained by off-line mathematical coverage analysis.

In the literature, some coverage analysis frameworks are available. In [3-4] and [8], mathematical frameworks for finding the minimum number of active sensor nodes required to cover a monitoring interest area guaranteeing the desired fractional coverage threshold are presented. The analytical frameworks are simple and the results obtained are tractable, but not accurate. The inaccuracy is resulted due to the adoption of the deterministic boolean sensing model, which mal-characterizes the detection capability of a sensor, in the analysis. In [2], a probabilistic Shadow-fading sensing model is presented to overcome the aforementioned inaccuracy. A mathematical expression to find the required number of sensor nodes for achieving the desired coverage threshold is then derived. The final expression obtained, however, is mathematically very complex; it does not have closed-form.

Hence, in this paper, we present the analysis adopting a new sensing model which basically is a hybrid of deterministic and probabilistic sensing models. The sensing model is good enough to accurately characterize the sensing behavior, and the final expression obtained for the minimum number of active sensors required to provide the desired coverage-threshold has a simple closed form.

The remainder of the paper is organized as follows. Motivation behind the current work is discussed in section 2. Review of some existing coverage analysis frameworks and their extensions are presented in section 3. Impacts of different sensing models are discussed in section 4. Finally, the paper is summarized in section 5.

Ⅱ. Motivation

In WSNs two types of redundancies, in context of number of activated sensor nodes, can be observed: beneficial redundancy and unwanted redundancy. First type of redundancy is generally preferred 1) to compensate the unawareness of exact location information of the sensor nodes, and 2) to offer fault tolerance which is especially desired in unattended working environment of sensor networks. However, the second type of redundancy is due to the inefficient pre-deployment coverage analysis. Most of such pre-deployment coverage analyses rely on simple on/off type (boolean) sensing model since analytical and asymptotic analyses carried with the deterministic model are simple and tractable. As the boolean sensing model assumes, however, it is unlikely that sensing capability of a sensor drops abruptly from the perfect detection capability to zero. This implies that there might be chances to detect an event occurring at distance greater than the specified sensing radius. By ignoring this extra sensing capacity, the boolean model cannot fully characterize the sensing capacity of the sensor. At the same time, it also results in spatial data redundancy (same event is sensed by adjacent nodes whose sensing ranges are spatially overlapped). Hence, coverage analysis carried incorporating the boolean sensing model results in activation of more redundant sensor nodes for the same desired coverage quality. Such redundant activations increase interferences and consequently decrease the life time of the sensor network. Hence, in this paper, we are motivated by the fact that the second type of redundancy can be nullified by making more accurate coverage analysis with more realistic sensing model.

Ⅲ. Coverage Analysis

Let us consider a WSN where large number of homogeneous sensor nodes are deployed with high node density over a regular 2-D geographical area. Furthermore, all the sensor nodes are supposed to be static. In such WSN, we are interested in finding the minimum number of sensor nodes required to cover a specified 2-D region with the desired fractional coverage indicator ψ.

We make some definitions as in [6] and [8]. Notations used in the analysis are tabulated in Table 1. Connectivity analysis is isolated from the present coverage analysis since under the well-agreed assumption (the radio range at least twice the sensing range) a complete coverage of a convex area implies connectivity among the set of working sensor nodes[7].

Definition 1: A Monitoring Interest Area, M, is the actual area of interest to be monitored by the selected subset of the deployed sensors. We consider this area as a square area with dimension $l \times l$.

Definition 2: A Sensor Deployment Boundary is a boundary for deployed sensors such that sensor with sensing radius of r residing on or within its perimeter has effect on sensing events occurring over M. The area bounded by this boundary is

Table 1. Definition of the notations used in the coverage analysis

Notation	Definition
D	Sensor deployment area: Boolean
D_e	Sensor deployment area: Hybrid
M	Monitoring interest area with dimension $l \times l$
M_{nc}	Area not covered by n sensors over M
P_i^{nc}	Probability that an event is not detected by i-th sensor
P^{nc}	Probability of not being covered by n sensors
ρ	Probability that S_i is located at (r, Θ) within D
ρ'	Probability that S_i is located at (r, Θ) within D_e
$P_x(r)$	Probability of any event being sensed at a distance r with model x
A	Area covered by S_i located at (r, Θ) with radius r_b
A'	Area covered by S_i located at (r, Θ) with radius $r_{\max}$
r_b	Boolean sensing radius
$r_{\max}$	Extended sensing radius beyond r_b
r_n	Sensing radius without considering fading
β	Decay factor
S_i	Selected sensor
ψ	Fractional coverage threshold
n	Number of selected sensors
χ	Gaussian variable used in Shadow- fading
σ^2	Variance of χ

sensor deployment area, D. The distance from any point along the edges of $M \subset D$ to sensor deployment boundary is r. Hence, the boundary is rectangular with rounded edges.

Definition 3: A Boolean Sensing Model is a function which characterizes the sensing behavior of a sensor as a probability of any event being sensed at a distance r as

$$p_b(r) = \begin{cases} 1 : 0 \le r \le r_b \\ 0 : r > r_b \end{cases} \tag{1}$$

Definition 4: An **Exponential Sensing Model** is a function which characterizes the sensing behavior of a sensor as a probability of any event being sensed at a distance r as

$$p_e(r) = \begin{cases} e^{-\beta r} : 0 \le r \le r_{max} \\ 0 : r > r_{max} \end{cases} \tag{2}$$

where β is the sensing decay factor and r_{max} is the maximum distance that the exponential sensing model can sense.

Definition 5: A **Shadow-fading Sensing Model** is a function which characterizes the sensing behavior of a sensor as a probability of any event being sensed at a distance r as

$$p_s(r) = Q(\frac{10\beta \log(r/r_n)}{\sigma}) \tag{3}$$

where r_n is the sensing radius without considering fading, $Q(Z)$ is the Q-function which can be represented as $Q(Z) = (1/\sqrt{2\pi}\int_z^{\infty} exp(-x^2/2)dx$, and x is a Gaussian variable with zero mean and σ^2 variance. This model is introduced in [2].

Definition 6: A **Hybrid Sensing Model** is a function which characterizes the sensing behavior of a sensor as a probability of any event being sensed at a distance r as

$$p_h(r) = \begin{cases} 1 : 0 \le r \le r_b \\ e^{-\beta(r-r_b)} : r_b < r \le r_{max} \\ 0 : r > r_{max} \end{cases} \tag{4}$$

This representation is simply a combination of boolean and exponential sensing model. In other words, it can be thought as a simplified Elfes sensing model in [5] with $\lambda = 1$. A heuristic approach to characterize the hybrid model with a staircase sensing function is discussed in [11].

Definition 7: A **Probabilistic Sensing Coverage** Ψ is a fractional coverage which is simply a ratio of the area covered by a set of the selected sensors to M. Equivalently, M is probabilistically covered by n sensors with $\Psi(0 \le \Psi \le 1)$ if $P(r,\theta) = 1 - \prod_{i=1}^{n} p_i^{nc}(r,\theta) \ge \psi$ for every point (r, Θ) in M, where $P(r, \Theta)$ is the collective probability from all n sensors to cover point (r, Θ) and $p_i^{nc}(r,\theta)$ is the probability that sensor i can not detect an event occurring at (r, Θ).

Graphical representation of the aforementioned sensing models are shown in Fig. 1.

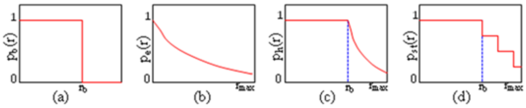

Fig. 1. Illustration of different sensing models: (a) Boolean, (b) Exponential, (c) Hybrid, and (d) Stair case approximation of Hybrid

3.1 Review of Coverage Analysis

Coverage analysis with deterministic boolean sensing model and probabilistic shadow-fading model is presented in [8] and [2], respectively. In this section, we review those analysis.

3.1.1 Analysis with Deterministic Boolean Sensing Model

Unlike the original analysis in [8], we present the analysis in polar coordinate system instead of cartesian coordinate system for the easy extension of this analytical framework to other probabilistic sensing models.

Let us assume that an event occurs at any point (r, Θ) within M. The event will be sensed if at least one sensor is present within circular area A centered at (r, Θ). Therefore the probability that the point (r, Θ) is not covered by a randomly selected sensor, s_i, can be calculated as

$$\begin{aligned} p_i^{nc}(r,\theta) &= 1 - \iint_{A(r,\theta)} \rho(r,\theta) p_b(r) r dr d\theta \\ &= 1 - \frac{1}{D}\int_0^{2\pi}\int_0^{r_b} r dr d\theta, \end{aligned} \tag{5}$$

where $D = l^2 + 4lr_b + \pi r_b^2$. For the uniformly and randomly distributed sensors, $\rho(r, \Theta) = 1/D$ is the probability that s_i is located at (r, Θ) within D. Hence eqn. (5) can be rearranged as

$$p_i^{nc}(r,\theta) = \frac{D - \pi r_b^2}{D}. \tag{6}$$

Hence, the probability that the point (r, Θ) is not covered by any of the n randomly selected sensors can be expressed as

$$P^{nc}(r,\theta) = \prod_{i=1}^{n} p_i^{nc}(r,\theta). \tag{7}$$

With the information of eqn. (7), the area not covered by n selected sensors within M, denoted as M_{nc}, can be estimated as

$$E[M_{nc}] = \iint_M P^{nc}(r,\theta) r dr d\theta. \tag{8}$$

Now, we are interested in calculating the fraction of M not covered by the selected n sensors. This value can simply be obtained by dividing $E[M_{nc}]$ by M. The fraction of M not covered by n selected sensors is derived to be

$$\frac{E[M_{nc}]}{M} = \left[\frac{D - \pi r_b^2}{D}\right]^n. \tag{9}$$

Finally, when n sensors are uniformly selected from D, the probabilistic sensing coverage Ψ that any point of M will be covered by at least one of the selected n sensors is given by

$$\psi = 1 - \frac{E[M_{nc}]}{M}. \tag{10}$$

Therefore, the smallest integer n which satisfies the desired Ψ can be expressed as

$$n = \left\lceil \frac{ln(1-\psi)}{ln\left(\frac{D - \pi r_b^2}{D}\right)} \right\rceil, \tag{11}$$

where $\lceil y \rceil$ is ceiling value of y. Hence, closed-form expression for the lower bound of the required number of sensors (when the deterministic boolean sensing model is considered) to satisfy the desired Ψ is obtained in eqn. (11).

3.1.2 Analysis with Probabilistic Shadow-fading Sensing Model

A probabilistic sensing model, Shadow-fading sensing model (Definition 5), is considered for the following analysis. $P^{nc}(r, \Theta)$ for the Shadow-fading model is obtained in [2], which is

$$P^{nc}(r,\theta) = \exp\left[\int_0^{r_{\max}} 2\pi\lambda[Q\left(\frac{10\beta \log_{10}(r_n / r)}{\sigma}\right) - 1]dr\right], \tag{12}$$

where λ is the average node density. Following the same reasoning and steps as from eqn. (8)-(11), smallest integer n which satisfies the required Ψ can be obtained easily. However, the final expression for n does not have closed-form expression as in the case of deterministic sensing model.

3.2 Extension of Coverage Analysis

The extension of the coverage analysis reviewed in the previous subsections is required due to the following reasons:

1) Deterministic (simple on/off type) boolean sensing model ignores the detection capability of a sensor at distances greater than the predefined sensing radius which, in practical scenario, is not always true. Hence, coverage analysis carried incorporating the deterministic sensing model results in activation of more redundant sensor nodes for the same desired coverage quality. Such redundant activations increase interferences and consequently decrease the life time of the

sensor network.

2) For accounting the problem stated in 1), analysis considering probabilistic Shadow-fading model is a good option. It reduces the redundancy in terms of number of sensors that could have introduced due to mal-characterization of sensing behaviour by the deterministic sensing model. However, the analysis does not have the close form expression like for the deterministic model. Hence pre-deployment analysis needs lots of computational effort.

Hence, in the following subsections, we present the extended coverage analyses with the some probabilistic sensing models which overcome the aforementioned problems.

3.2.1 Analysis with Probabilistic Exponential Sensing Model

Likewise in previous analysis, let us assume that an event occurs at (r, Θ) within M. The event will be sensed with probability $p_{e(r)}$ if at least one sensor is present within circular area A' centered at (r, Θ) with radius $r_{\max} > r_b$. Therefore the probability that the point (r, Θ) is not covered by a randomly selected sensor, s_i, is given by the following relation

$$p_i^{nc}(r,\theta) = 1 - \iint_{A'(r,\theta)} \rho'(r,\theta) p_e(r) r dr d\theta$$
$$= 1 - \frac{1}{\mathsf{D}_e} \int_0^{2\pi} \int_0^{r_{max}} r e^{-\beta r} dr d\theta, \qquad (13)$$

where $D_e = l^2 + 4lr_{\max} + \pi r_{\max}^2$. For the uniformly and randomly distributed sensors, $\rho'(r, \Theta) = 1/D_e$. After further mathematical simplifications, eqn. (13) can be rewritten as

$$p_i^{nc}(r,\theta) = \frac{\mathsf{D}_e\beta^2 - 2\pi\{1 - e^{-\beta r_{max}}(1 + \beta r_{max})\}}{\mathsf{D}_e\beta^2}. \qquad (14)$$

With the similar analysis, as carried for the deterministic boolean sensing model, and after further simplification , we get

$$n = \left\lceil \frac{ln(1-\psi)}{ln[\frac{\mathsf{D}_e\beta^2 - 2\pi\{(1 - e^{-\beta r_{max}}(1 + \beta r_{max}))\}}{\mathsf{D}_e\beta^2}]} \right\rceil \qquad (15)$$

Hence, closed-form expression for the lower bound of the required number of sensors (when exponential sensing model is considered) to satisfy the desired Ψ is obtained in eqn. (15).

3.2.2 Analysis with Probabilistic Hybrid Sensing Model

Let us assume that an event of sensing interest occurs at (r, Θ) within M. The event will be sensed with probability $p_{h(r)}$ if at least one sensor is present within circular area A' centered at (r, Θ) with radius $r_{\max}$. Therefore, the probability that the point (r, Θ) is not covered by a randomly selected sensor, s_i, is given by the following relation

$$p_i^{nc}(r,\theta) = 1 - \iint_{A'(r,\theta)} \rho'(r,\theta) p_h(r) r dr d\theta \qquad (16)$$
$$= 1 - \frac{1}{\mathsf{D}_e}\left[\int_0^{2\pi}\int_0^{r_b} r dr d\theta + \int_0^{2\pi}\int_{r_b}^{r_{max}} r e^{-\beta(r - r_b)} dr d\theta\right]$$

After further mathematical simplification, eqn. (16) can be rewritten as

$$p_i^{nc}(r,\theta) = \frac{\mathsf{D}_e\beta^2 - \pi\beta^2 r_b^2 - 2\pi\{(1+\beta r_b) - e^{-\beta(r_{max} - r_b)}(1 + \beta r_{max})\}}{\mathsf{D}_e\beta^2}. \qquad (17)$$

Following the similar analysis as in eqn. (6)-(9) the fraction of M not covered by n selected sensors is derived to be

$$\frac{E[\mathsf{M}_{nc}]}{\mathsf{M}} = \left[\frac{\mathsf{D}_e\beta^2 - \pi\beta^2 r_b^2 - 2\pi\{(1+\beta r_b) - e^{-\beta(r_{max} - r_b)}(1 + \beta r_{max})\}}{\mathsf{D}_e\beta^2}\right]^n. \qquad (18)$$

The probabilistic sensing coverage, Ψ, that any point of M will be covered by at least one of the selected n sensors is given by

$$\psi = 1 - \left[\frac{D_e\beta^2 - \pi\beta^2 r_b^2 - 2\pi\{(1+\beta r_b) - e^{-\beta(r_{max}-r_b)}(1+\beta r_{max})\}}{D_e\beta^2}\right]^n . \quad (19)$$

Therefore, the smallest integer n which satisfies the desired Ψ can be expressed as

$$n = \left\lceil \frac{ln(1-\psi)}{ln\left[\frac{D_e\beta^2 - \pi\beta^2 r_b^2 - 2\pi\{(1+\beta r_b) - e^{-\beta(r_{max}-r_b)}(1+\beta r_{max})\}}{D_e\beta^2}\right]} \right\rceil \quad (20)$$

Hence, closed-form expression for the lower bound of the required number of sensors (when hyprid sensing model is considered) to satisfy the desired Ψ is obtained in eqn. (20).

Ⅳ. Results and Discussion

In this section, we present a detailed analysis for the impact of different sensing models: boolean, exponential, hybrid Boolean-exponential and Shadow-fading on coverage with aid of some numerically obtained results from the equations derived in the previous section. The analysis of sensing coverage is carried in the following three dimensions:

Different monitoring area size: Firstly, we analyze Ψ for different M considering a set of fixed sensing parameters for all the four considered sensing models. For the Boolean model r_b is fixed to 20 m while for the exponential and hybrid model r_{max} and β are fixed to 30m and 0.1, respectively. For the Shadow-fading model σ of the χ is fixed to 4 and r_n is assumed to be equal to r_b. With the increase in M from $1000\times1000m^2$ to $1500\times1500m^2$, required n to guarantee the same desired Ψ increases, for all sensing models, as can be noted in Fig. 2 (a). For satisfying the same Ψ for a given M, required n obtained from the analysis considering hybrid sensing model is significantly less in comparison to the n obtained from the analysis considering boolean sensing model. It can

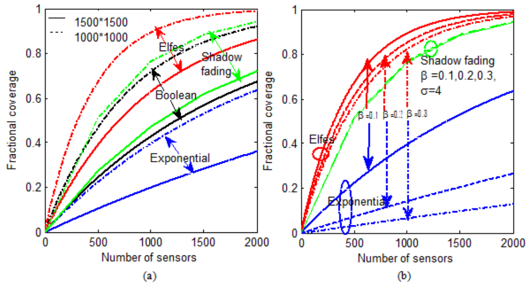

Fig. 2. Fractional coverage analysis: (a) Different M with fixed sensing parameters, and (b) Different decay parameters with fixed M

be interpreted that the boolean model mal-characterizes the sensing behaviour and suggested higher n than actually required, provided that the hybrid sensing model perfectly characterizes the sensing behaviour. Shadow-fading model reduces the redundancy slightly but not effectively as hybrid sensing model.

Different decay factor for sensing signal: All the sensing model parameters are taken as previously discussed except β is varied and M is taken to be $1000\times1000\,m^2$. With increase in β, required n to guarantee a certain Ψ is increased for both the analysis which assumed the exponential and the hybrid sensing models, as can be noted in Fig. 2 (b). Impact of β is higher in the exponential sensing model compared to the hybrid sensing model while for the shadow-fading model there is no significant effect. However, this current observation with varying β does not perfectly express the exact effect of decay factor on hybrid sensing model since effect of β hugely depends on the r_{max}/r_b ratio as well. In the hybrid sensing model, the higher the ratio is, the higher will be the distance over which sensing signal decays.

Different ratio of r_{max}/r_b: The ratio can be increased either by increasing r_{max} for a fixed r_b or by decreasing r_b for the fixed r_{max}. For the analysis, we increased the ratio in both ways. Firstly r_b is lowered to 15 m keeping r_{max} constant, and secondly r_{max} is increased to 35 m keeping r_b constant for the same β. As can be noted in Fig. 3 (a) and Fig. 3 (b), the higher the r_{max}/r_b ratio is, the more will be the decay effect and more number of sensor nodes will be needed for guaranteeing the desired fractional coverage. It Is noteworthy to mention that same amount of increase in r_b and r_{max}, separately one at a time, have different magnitude of effect in coverage performance as can be compared between two pair of curves in Fig. 3(a) and Fig.3(b), respectively. Hence, for the coverage analysis, value of r_b and r_{max} should be chosen in such a way that decay characteristics can be captured well. When $r_{max}/r_b \rightarrow 1$ the result of the hybrid sensing model will be almost similar to result of the boolean sensing model.

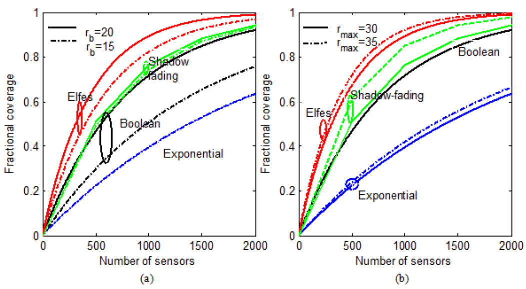

Fig. 3. Fractional coverage analysis: (a) Different r_b with constant M=1000×1000m^2, $r_{max}=30m$ and β=0.1, and (b) Different r_{max} with constant M=1000×1000m^2, $r_b=20m$ and $\beta=0.1$

Ⅴ. Conclusion

Coverage analysis of a randomly deployed sensor network considering different deterministic and probabilistic sensing models is reviewed and the analysis is extended with the more accurate hybrid sensing model. The extended analysis offers a closed-form expression to calculate the required number of sensor nodes to guarantee the desired sensing coverage threshold. Through the detailed analytical performance comparison, the redundancy (in terms of number of required sensor nodes) resulted due to the detection capability mal-characterizing sensing models is demonstrated. The extended analytical framework can be used as a tool for the coverage analysis of the network prior to deployment, and for the design of density control algorithms for post-deployment network management.

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