An Efficient Sensor Deployment Scheme for Large-Scale Wireless Sensor Networks

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***Abstract*—Sensor deployment to achieve better system performance is one of the critical issues in wireless sensor networks. An effective sensor deployment scheme is proposed for large-area sensor networks, where the event occurrence rate varies over the sensor-deployed region. By utilizing the local event occurrence rate and applying the analytical sensor detection capability expression for the problem formulation, the proposed scheme determines the optimal number of sensors for a typical surveillance sensor network that should be deployed in each local region that minimizes the total number of sensors while satisfying the target probability of the overall detection. The optimality of the proposed scheme is examined, and it is also shown that the sensor deployment by the proposed scheme considerably reduces the total number of sensors in comparison with a conventional sensor deployment.**

***Index Terms*—Large-scale sensor networks, event incident rate, cognitive wireless sensor networks, distributed resource allocation.**

I. Introduction

A WIRELESS sensor network (WSN) is composed of a large number of very small, low-cost sensor nodes, which can freely communicate over short distances [1]. The sensor nodes of WSN are spatially distributed sensors for monitoring environmental conditions or events of concern, and cooperatively pass their data through the network to a main location [2]–[4].

One of the critical issues of WSN is how the sensors are efficiently deployed while achieve the required detection performance [5]. Most of previous works on sensor deployments have investigated uniform sensor deployments based on regular environments of deployment areas. In one study, a grid-based uniform sensor deployment scheme was proposed [6]. The scheme places sensors at each grid point, and determines the grid distance that minimizes the number of sensors while still guaranteeing the detection capability.

As a number of typical WSN applications such as surveillance or environmental monitoring are likely to expand their service coverage, the sensor deployment for large-scale sensor networks has been getting much attention [7]–[9]. In such large-scale sensor networks, the environments can vary in different localities, so more efficient deployment can be developed with the local environment information. In this aspect, a local information assisted sensor deployment which utilizes region-dependent sensor connectivity distances was proposed [10]. Other than the sensor connectivity distances, event occurrence rates may not be the same over the whole area in large-scale sensor networks, so more efficient sensor deployments for large-scale sensor networks can be expected by using Fig. 1. System model this information. With this consideration, a sensor deployment scheme with assistance of local event occurrence rate information in order to maximize the overall detection capability for the given number of sensors was suggested [13].

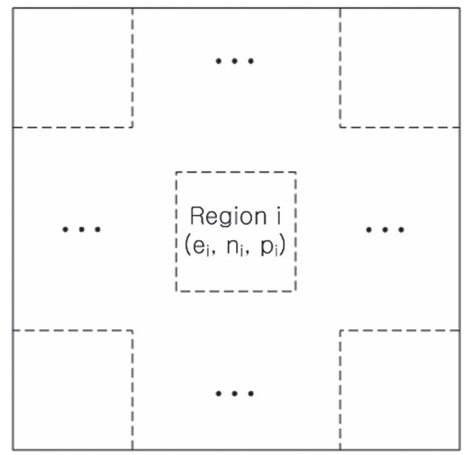

Fig. 1. System model.

This work provides a new approach for minimization of the number of sensors for the large-scale sensor networks. The local incidence rate information and an analytical sensor detection capability equation being utilized, an optimization problem for minimization of the number of sensors is formulated. By solving the problem, an optimal sensor deployment for the large-scale sensor networks is proposed, so an enhanced cost-efficient large-scale sensor deployment scheme can be derived from this approach.

The rest of the letter is organized as follows. In Section II, the system model for a large-scale sensor networks and related assumptions will be described. And then an optimal problem for sensor deployment is formulated, followed by the sensor deployment algorithm to find an optimal solution of sensor deployments is addressed in Section III. In Section IV, simulation results that indicate the proposed scheme outperforms a conventional scheme will be provided. Finally, conclusions will be presented in Section V.

II. System Description

This letter considers sensor deployments over a wide area with N local regions as shown in Fig. 1. Each local region can be characterized by its event incident rate, e_i, and will be covered

Manuscript received October 13, 2014; revised November 9, 2014; accepted November 14, 2014. Date of publication November 20, 2014; date of current version January 7, 2015. This work was supported by Incheon National University Research Grant in 2011. The associate editor coordinating the review of this paper and approving it for publication was A. Rabbachin. *(Corresponding author: Sang-wook Han.)*

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Digital Object Identifier 10.1109/LCOMM.2014.2372015

by n_i sensors. As examined in [11], the system of a surveillance sensor network for detecting a target crossing the total area is considered. Let L be the perimeter of the local regions. A sensor detection capacity for heterogeneous sensors in large networks is derived as $1 - e^{\sum_j (l_j/L)}$, where l_j is the sensing range perimeter of the sensor j [11]. This work assumes the same sensing range perimeter of sensors as l, so the detection probability for region i with n_i sensors can be represented by

$$p_i = 1 - e^{-\sum_1^{n_i} \frac{l}{L}}. \tag{1}$$

Let P_{det} denote the overall detection probability for the whole region, which is computed by

$$P_{\text{det}} = \sum_i e_i \cdot p_i. \tag{2}$$

It is a challenge of sensor deployments maintain the average detection probability of systems requirements with a reduced number of sensors.

III. Sensor Deployment Schemes

This section addresses the minimization of the number of sensors with provision of the required overall detection capability based on the local event occurrence rate while applying the sensor detection capability of (1). Determining the number of sensors in each region is a discrete problem. This work develops a simple approach with a relaxation of the problem to be a continuous problem. Firstly, the case for uniform deployment is examined, and then an optimal sensor deployment that achieves the minimization by an efficient use of the local information is provided.

A. Uniform Deployment

The uniform sensor deployment places the same number of sensors in each sub-region. Let n_i be the number of sensors in region i. Then, the condition to meet the average required detection probability P_{req} is:

$$\sum_i^N e_i \cdot \left(1 - e^{-\sum_1^{n_i} \frac{l}{L}}\right) \geq P_{\text{req}}. \tag{3}$$

Since $\sum_i^N e_i = 1$, n_i for the uniform deployment can be obtained by

$$n_i = \frac{L}{l} \ln(1 - P_{\text{req}}), \tag{4}$$

B. Proposed Deployment

An optimization problem P_o to determine the number of sensors for each region while achieving the minimum total number of sensors with the constraint of required average detection probability is formulated as

$$\text{P}_\text{o} : \text{Minimize}_{n_i' s} \quad \sum_i^N n_i \tag{5}$$

$$\text{s.t.} \quad \sum_i^N e_i \cdot p_i \geq P_{\text{req}}, \tag{6}$$

$$n_i \geq 0 \quad (i = 1, 2, \ldots, N), \tag{7}$$

where (7) is the objective function for minimizing the total number of sensors deployed over all local regions, and (8) is a constraint that the average detection probability over all local regions should be less than or equal to a target value. p_i in (8) can be substituted with the right side of (2) and $\sum_i^N e_i = 1$. Then, P_o is rewritten as

$$\text{P}_\text{o} : \text{Minimize}_{n_i' s} \quad \sum_i^N n_i \tag{8}$$

$$\text{s.t.} \quad \sum_i^N e_i \cdot e^{-\frac{l}{L} n_i} \leq 1 - P_{\text{req}} \tag{9}$$

$$n_i \geq 0 \quad (i = 1, 2, \ldots, N). \tag{10}$$

For given l, L, e_i's and P_{req}, n_i can be found by solving P_o, but it is non-trivial to solve P_o. Let x_i and y be substituted by $e_i \cdot e^{-\frac{l}{L} n_i}$ and $1 - P_{\text{req}}$, respectively, and n_i be replaced with $\frac{L}{l} ln \frac{e_i}{x_i}$. Then, P_o changes to P_o' as below.

$$\text{P}_\text{o}' : \text{Minimize}_{x_i' s} \quad \sum_{i=1}^N \frac{L}{l} \ln \frac{e_i}{x_i} \tag{11}$$

$$\text{s.t.} \quad \sum_i^N x_i \leq y. \tag{12}$$

$$0 \leq x_i \leq e_i \quad (i = 1, 2, \ldots, N). \tag{13}$$

l, L and e_i are non-negative and assumed to be known, so the objective function in P_o' may change to Minimize $\sum_i -\ln x_i$, which is equivalent to Maximize $\sum_i \ln x_i$. So, P_o' changes to:

$$\text{P}_\text{o}' : \text{Maximize}_{x_i} \quad \sum_i \ln x_i \tag{14}$$

$$\text{s.t.} \quad \sum_{i=1}^N x_i \leq y \tag{15}$$

$$0 \leq x_i \leq e_i \quad (i = 1, 2, \ldots, N). \tag{16}$$

P_o' is a convex problem because (14) is a concave function, and (15) and (16) are convex sets. Therefore, there exists a global optimal solution for this problem. The Lagrangian is represented as

$$L(\mathbf{x}, \lambda) = \sum_{i=1}^N \ln x_i - \lambda \left(\sum_{i=1}^N x_i - y \right) - \sum_{i=1}^N \mu_i (x_i - e_i) \tag{17}$$

where λ and μ_i's are the nonnegative Lagrange multipliers. Taking the derivatives with respect to x_i and the multipliers gives the Karush-Kuhn-Turker (KKT) condition as follows.

$$\frac{\partial L(\mathbf{x}, \lambda)}{\partial x_i} = \frac{1}{x_i} - \lambda - \mu_i = 0 \quad (i = 1, 2, \ldots, N) \tag{18}$$

$$x_i \left(\frac{1}{x_i} - \lambda - \mu_i \right) = 0 \quad (i = 1, 2, \ldots, N) \tag{19}$$

$$\lambda \left(\sum_{i=1}^N x_i - y \right) = 0 \tag{20}$$

$$\mu_i (x_i - e_i) = 0 \quad (i = 1, 2, \ldots, N). \tag{21}$$

This problem is regarded as finding the maximum product of x_i's, which can be obtained by identical x_i's for unconstrained condition. However, it requires additional consideration when there are constraints resulting in the solution out of the feasible region. It can be noticed that (20) acts as an active constraint while (21) acts either active or inactive constraints depending on the system parameters. The KKT condition indicates that those x_i's with positive μ_i's are set to e_i's while the other x_i's are identically set to $\frac{y-\sum_{i\in M} e_i}{N-|M|}$, where M is the set of i's whose μ_i's are positive.

Suppose that e_i's are indexed in ascending order. When $\frac{y}{N}$ is smaller than all e_i's, the optimal x_i's are identically determined by $\frac{y}{N}$. On the other hand, for example, if e_1 and e_2 are smaller than $\frac{y}{N}$ and the other e_i's are greater than $\frac{y}{N}$, x_1 and x_2 are set to e_1, and e_2, respectively, while the other e_i's are required to be checked if they are larger than the sum constraint updated to, $\frac{y-e_1-e_2}{N-2}$. Once x_i is set to e_i during this process, its solution is not changed because the value to be compared with e_i's in the next iteration increases due to the additional exclusion of x_i's smaller than the current value in computing the comparison value. So provided x_1 and x_2 are determined, the optimization problem becomes the maximization of the product for the remaining x_i's except x_1 and x_2 with the sum constraint updated to $\frac{y-e_1-e_2}{N-2}$. When e_3 and all the other e_i's for the remaining x_i's are greater than $\frac{y-e_1-e_2}{N-2}$, the remaining x_i's are determined by $\frac{y-e_1-e_2}{N-2}$. Otherwise, another similar computation is required to find the optimal solution for the remaining x_i's. We suggest an algorithm to find the optimal x_i's as below. Note that X is the set of i's whose x_i's is over the comparison value at each iteration.

Initialization step

1: Set $x_i = y/N$
2: Set $X = \{i|x_i > e_i\}$

Iteration step

3: **While** $(X \neq \phi)$
4: $\quad y = y - \sum_{i\in X} x_i$ and $N = N - |X|$
5: $\quad$ **If** $i \in X$, set $x_i = e_i$
6: $\quad$ **Else** update $x_i = \frac{y}{N}$
7: $\quad$ **End**
8: $\quad$ Update $X = \{i|x_i > e_i\}$
9: **End**

IV. Performance Evaluation

A. Simulation Environment

This section presents the performance evaluation of the sensor deployment designed by the proposed scheme, investigating the average event detection probability and the total number of sensors as a performance measure. The proposed scheme is compared with the uniform deployment algorithm, which places sensors uniformly over the regions selecting n_is equivalently as (4). It is assumed that L is four or five times the value of l, and e_is are known beforehand. This work considers large-scale sensor networks, where the local event occurrence rate may appear differently over the regions. In order to reflect different levels of the variance of the local event occurrence rate, a simple probability mass function for e_i's is chosen which is represented by $a(i-\frac{N+1}{2})+\frac{1}{N}$. Note that by varying a from 0 to $\frac{2}{N(N-1)}$, e_i's are non-negative and monotonically increased by a, while the sum and the average are maintained to 1 and $\frac{1}{N}$, respectively. The variance of e_i's become the maximum when a is $\frac{2}{N(N-1)}$.

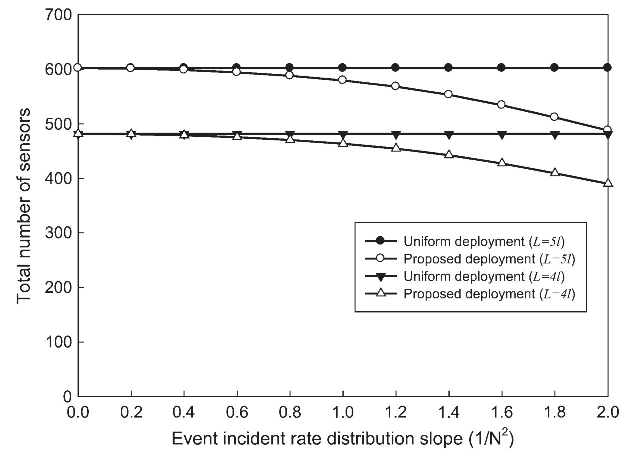

Fig. 2. Total number of sensors versus event incident rate distribution slope.

B. Simulation Results

From (4) and the solution for the proposed scheme, it is expected that more sensors per region are required per region for larger values of $\frac{L}{l}$ and P_{det}. On the other hand, N alone does not affect the number of sensors per region. This is because the fact that the sum of e_i's is 1 offsets any change of N in determining the number of sensors in a region. Of course the total number of sensors increases as N grows. Regarding the geometry of the area, simply a squared type of local regions is assumed, so the area/perimeter ratio in a region would be $\frac{(L/4)^2}{L}$ which becomes $\frac{L}{16}$. The impact of L can be inferred by that of L for the given l, that is, from the understanding of the impact of $\frac{L}{l}$, it is expected the required number of sensors in a region grows as the area/perimeter increases. Please note that the total area can be considered as just a combination of the local regions, of which the shape itself does not affect the system performance because e_i's are assumed to be set separately in this paper. The value for N is set to 10 in the performance evaluation.

In Fig. 2, the total number of sensors with different variance of e_i is shown. L is set by $4l$ or $5l$, and P_{req} is assumed to be 0.7. The evaluation result shows that the total number of sensors with uniform deployment is reduced by employing the proposed deployment scheme. Provided the same P_{req}, there is no change in the total number of sensors when the uniform deployment is applied. In contrast to the case of uniform

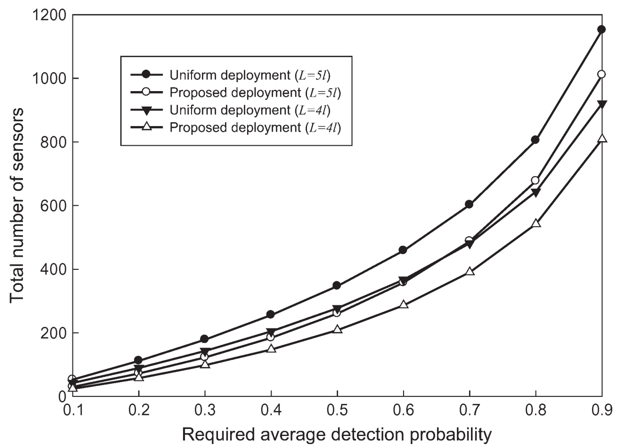

Fig. 3. Total number of sensors versus average required detection probability.

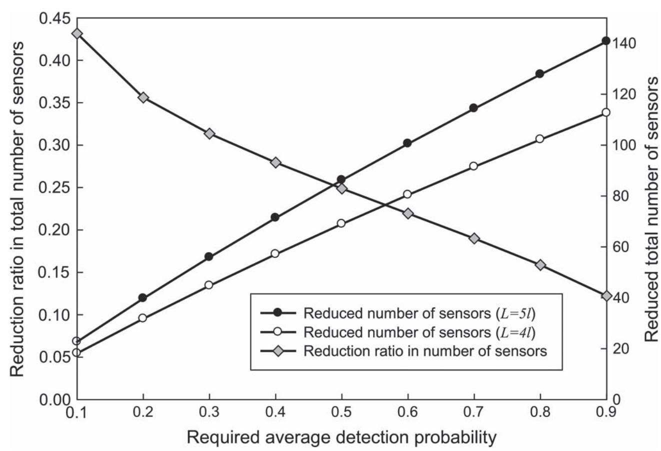

Fig. 4. Reduced total number of sensors and reduction ratio in total number of sensors versus average required detection probability.

deployment, the total number of sensors for the proposed deployment scheme decreases as the variance of e_is increases. This is because the proposed deployment utilizes the event incident rate of each region for the enhancement of deployment efficiency to reduce the total number of sensors, which is not utilized for the uniform deployment. More sensors are required for an L value of $5l$ than the case of $4l$, because the larger L results in more sensors required to cover a sub-region.

Fig. 3 shows the total number of sensors for different values of required average detection probability. The L values of $4l$ and $5l$ are considered, while a is set to $\frac{2}{N^2}$. As P_{req} increases, more sensors are required to satisfy the increased average detection requirement. It can be seen that the proposed deployment achieves the required detection performance with fewer sensors than the uniform deployment, and the gap in performance increases as the requirement level is raised.

Fig. 4 shows the number of sensors reduced by the proposed deployment compared to the uniform deployment in the same scenario as in Fig. 3. The gap of the number of sensors between the two deployment schemes is shown more clearly. The reduction ratio, defined by $1 - \frac{n_u}{n_i^*}$, is also shown, and a value of around $10\% \sim 40\%$ is attained for the given conditions.

V. Conclusion

A deployment scheme that satisfies the average detection probability requirements for large-scale WSNs has been suggested. In contrast to the uniform deployment scheme, the proposed scheme considers the local event incidence rate information in sensor deployment. An optimal problem has been suggested to determine the number of sensors for each local region that minimizes the total number of sensors while satisfying the requirements for average detection probability, and an algorithm to find the optimal solution has been proposed. The simulation results showed that the proposed algorithm achieves efficient sensor deployment under the scenario considered. Further works will include the integer problem approach, the performance evaluation with imperfect event incidence rate information, the consideration for more general sensor capabilities and diverse shapes of regions.

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