Central Angle Decision Algorithm in Coverage-Preserving Scheme for Wireless Sensor Networks

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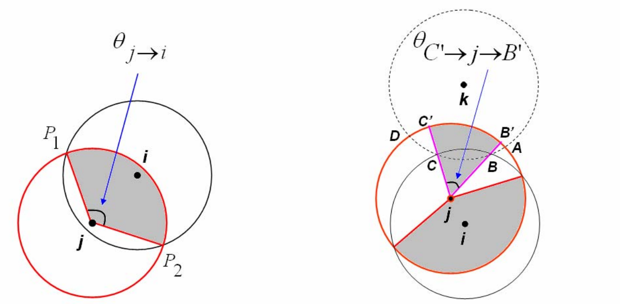
***Abstract*—In wireless sensor networks, energy efficiency is a key design factor to prolong the network lifetime. Recently, Optimal Coverage-Preserving Scheme (OCoPS) is proposed in [7] as an extension of the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol with the coverage-preserving scheme which saves energy consumption through excluding redundant nodes of which sensing ranges are fully overlapped by their on-duty neighbors. Nevertheless, in some stringent applications such as battlefield surveillance, fire detection, and toxic liquid leaking detection, the higher network coverage quality is also strictly required. In this paper, we propose the central angle decision algorithm (CADA) which guarantees no coverage-hole during the coverage-preserving scheme. To evaluate applicability of our proposed algorithm to routing protocols and its performance, we extend the OCoPS routing protocol with CADA, namely, the Optimal Coverage-Preserving Scheme with the Central Angel Decision Algorithm (OCoPS_CADA). Extensive simulations show that the OCoPS_CADA outperforms the OCoPS by initially guaranteeing 100% of the network coverage.**

I. INTRODUCTION

Wireless sensor network (WSN) is a good candidate for applications such as battlefield surveillance, environmental monitoring, patients monitoring, and inventory managing [1][2][3]. In WSNs, one of the most significant constraints is the limited battery power of the nodes since the deployed nodes are infeasible to be recharged or be replaced once they are deployed in an unattended area. In this regard, it is worthwhile to pursue energy efficiency in WSNs. To achieve energy efficiency, excluding redundant nodes from on-duty mode for replacing dead nodes later is a well known strategy. Due to dense deployment in WSNs, redundant nodes exist in a network, in which sensing ranges are fully overlapped by their on-duty neighbors. By reducing the redundant nodes without loosing the overall sensing coverage, as well as maintaining certain system reliability, significant energy saving can be achieved [4]. To eliminate the redundant nodes, the coverage-preserving scheme is a good solution. To solve this problem, Tian at al. in [5] devise the Central Angle Calculation (CAC) scheme, which is a novel approach calculating the central angle of nodes instead of the coverage area to decide whether a sensor node can be off-duty or not, and an extension of the LEACH routing protocol [6] with the CAC scheme named as the Coverage-Preserving Node Scheduling Scheme (C-PNSS). In the C-PNSS routing protocol, a global clock synchronization is required to solve the off-duty conflict problem, which generates coverage-holes when all nodes make off-duty decisions simultaneously. The random back-off scheme, which uses random time delay to make the off-duty decisions, does not guarantee no coverage-hole after turning some sensor nodes off.

Boukerche at al. in [7] propose the Extended Central Angle Calculation (ECAC) scheme which extends the CAC scheme to save more energy. They devise an extension of the LEACH routing protocol with the ECAC scheme named as the Optimal Coverage-Preserving Scheme (OCoPS) routing protocol, which solves the off-duty conflict problem with the help of additional control messages. Since the ECAC additionally considers another node of which distance from the coverage calculation target node is bigger than the sensing radius and smaller than twice of the sensing radius, more nodes can be turned off than using the CAC scheme. As a result, OCoPS with the ECAC scheme increases the network lifetime approximately 20% more than C-PNSS with the CAC scheme. An important question that arises, however, is whether the ECAC scheme would generate a coverage-hole. In some stringent applications such as battlefield surveillance, fire detection, and toxic liquid leaking detection, where even a small coverage-hole can jeopardize the overall network coverage quality or the derived event detection delay from the coverage-hole can cause the greater damage, the higher network coverage rate is strictly required.

In order to solve the problem which causes coverage-holes and the derived event detection delays, we define the angle decision problem of the ECAC scheme as selecting a right angle among the four possible choices without any coverage-hole and propose a central angle decision algorithm (CADA) to select the right one and guarantee no coverage-hole in the network. In order to evaluate applicability of our proposed algorithm to routing protocols and expected performance of the algorithm, we devise an extension of the OCoPS routing protocol with CADA named as the Optimal Coverage-Preserving Scheme with the Coverage Angle Deci-



$(a)\ \ \theta_{j\to i}$ $(b)\ \ \theta_{j\to i}$ and $\theta_{C'\to j\to B'}$

Fig. 1. Sponsored angle calculation - (a) CAC and (b) ECAC schemes

sion Algorithm (OCoPS_CADA) and compare OCoPS_CADA with OCoPS. This paper is organized as follows. We describe previous works on coverage-preserving schemes and the central angle decision problem, derive decision rules, and provide our devised algorithm in Section II. In Section III, we outline the network model and radio model for our simulation. In Section IV, we evaluate the performance of our algorithm through analysis of the simulation results. Finally, we conclude this paper.

II. THE CENTRAL ANGLE DECISION ALGORITHM (CADA)

In this section, we describe our devised algorithm and its background. In the first part of this section, we describe previous works. In the second part, we define the central angle decision problem. In the third part, we derive the decision rules. In the fourth part, we propose CADA.

A. Previous Works

The purpose of the coverage calculation is to find redundant nodes in which sensing ranges are fully overlapped or sponsored by their on-duty neighbors. CAC [5] is a novel scheme where off-duty nodes are calculated through the sponsored central angles of the nodes instead of overlaid areas. With using the angle antenna, such a scheme can resolve the coverage problem [5]. For example, tn Fig. 1(a), the overlaid area can be calculated as the shaded crescent area, the area can be calculated as the central angle, and the angle can be calculated by the equations below.

$$\theta_{j\to i} = 2\arccos\left(\frac{d(i,j)}{2r}\right) \tag{1}$$

where $\theta_{j\to i}$ denotes the sponsored angle of node j referred to node i, $d(i,j)$ denotes the distance from node i to node j, and r denotes the sensing radius of each sensor node [5].

$$\phi_{j\to i} = \arctan\left(\frac{Y_i - Y_j}{X_i - X_j}\right) \tag{2}$$

where $\phi_{j\to i}$ denotes the direction of node j referred to node i and X_i, Y_i, X_j, and Y_j denote coordinates for sensor i and j respectively [5].

Although the CAC scheme is useful in determining the crescent area as a central angle and its direction, it is also limited in that the CAC scheme only considers the cases where the distance between two nodes is less than or equal to the single sensing radius. As shown in Fig. 1(b), CAC scheme cannot calculate the upper shaded angle on node j by node i and k. As a result, more nodes in the network will be awake than necessary. To calculate the shaded angle, Boukerche et al. devise the ECAC scheme in [7]. As made clear in the Fig. 1(b), the upper shaded angle can be calculated as follows. In the intersection point C of sensors i and k, the coordinates of sensor i and k are known, so, $\phi_{k\to i}$ and $\theta_{k\to i}$ can also be calculated by (1) and (2) respectively. Thus, the coordinates of C can be calculated as follows: $X_C = X_i + r * \cos(\phi_{k\to i} + \theta_{k\to i}/2)$ and $Y_C = Y_i + r * \sin(\phi_{k\to i} + \theta_{k\to i}/2)$. Coordinates of B can be calculated in the same way. After computing of B coordinates, we can calculate the sponsored angle $\theta_{C'\to j\to B'} = \arctan((Y_C - Y_j)/(X_C - X_j) - (Y_B - Y_j)/(X_B - X_j))$.

B. Central Angle Decision Problem

As shown in Fig. 2, when we calculate the upper shaded angle by the ECAC scheme, there are four possible shaded angle cases: $\theta_{C'\to j\to A}$, $\theta_{D\to j\to B'}$, $\theta_{D\to j\to A}$, and $\theta_{C'\to j\to B'}$. By the relative positions of three nodes, one of four can be the right angle selection. For example, in Fig. 2(a), selecting $\theta_{C'\to j\to A}$ is a right angle decision, but without any decision algorithm, ECAC scheme can select a wrong angle among $\theta_{D\to j\to B'}$, $\theta_{D\to j\to A}$, and $\theta_{C'\to j\to B'}$. By selecting the wrong angle, coverage-holes arise in the network. Since the holes degrade the network coverage quality and the derived event detection delays cause the greater damage for the target applications, a central angle among the four should be rightly selected. Thus, we define the central angle decision problem as selecting a right angle among the four choices. To solve the central angle decision problem, we devise the decision rules and algorithm in the next subsection.

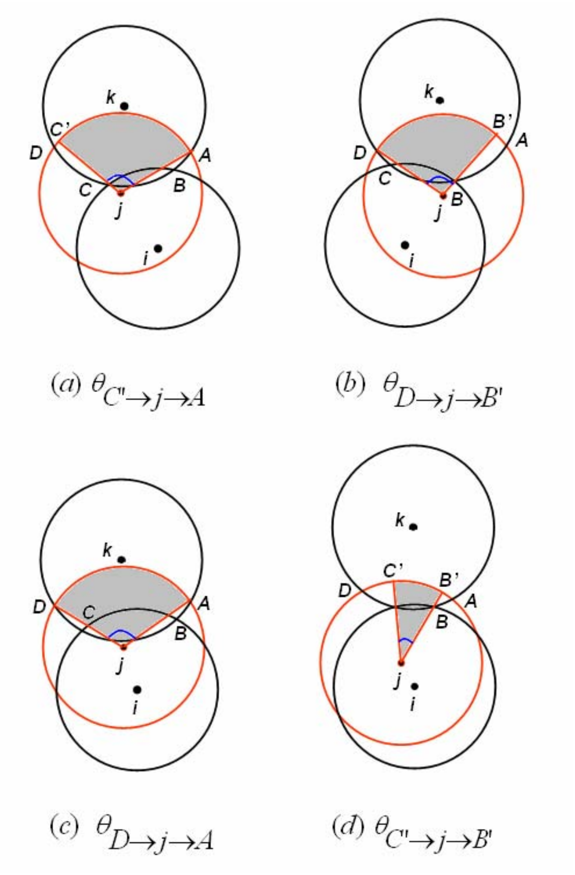
C. Decision Rules

It is clear from Fig. 2(a) that the minimum angle among the four angles is the right angle we need. To make the problem simpler, we first compute $\min\ \{\ \theta_{C'\to j\to k},\ \ \theta_{D\to j\to k}\}$, secondly compute $\min\ \{\ \theta_{k\to j\to B'},\ \theta_{k\to j\to A}\ \}$, and finally add the two angles to calculate $\min\ \{\theta_{C'\to j\to A},\ \ \theta_{D\to j\to B'},\ \ \theta_{D\to j\to A}, \theta_{C'\to j\to B'}\}$. To compute the first minimum angle, we derive the first decision rule below.

$$\angle C'jk \underset{min\theta\ =\ \angle Djk}{\overset{min\theta\ =\ \angle C'jk}{\lesseqgtr}} \angle Djk \tag{3}$$

where $\angle C'jk$ and $\angle Djk$ are the left two angels in Fig. 2. Given the coordinates for sensor i, j, and k, we can compute the two angles as below.

$$\angle C'jk = \arctan\left(\frac{Y_C - Y_i}{X_C - X_i}\right) - \arctan\left(\frac{Y_k - Y_i}{X_k - X_i}\right) \tag{4}$$



(a) $\theta_{C''\to j\to A}$ (b) $\theta_{D\to j\to B'}$

(c) $\theta_{D\to j\to A}$ (d) $\theta_{C''\to j\to B'}$

Fig. 2. Four possible central angle cases

where $X_C = X_i + r\cos(\phi_{i\to k} + \theta_{i\to k}/2)$ and $Y_C = Y_i + r\sin(\phi_{i\to k} + \theta_{i\to k}/2)$.

$$\angle Djk = \arctan\left(\frac{Y_D - Y_i}{X_D - X_i}\right) - \arctan\left(\frac{Y_k - Y_i}{X_k - X_i}\right) \tag{5}$$

where $X_D = X_j + r\cos(\phi_{j\to k} + \theta_{i\to k}/2)$ and $Y_D = Y_j + r\sin(\phi_{j\to k} + \theta_{i\to k}/2)$. By the (3), (4), and (5),

$$\arctan\left(\frac{Y_C - Y_i}{X_C - X_i}\right) \underset{min\theta\ =\ \angle Djk}{\overset{min\theta\ =\ \angle C'jk}{\lessgtr}} \arctan\left(\frac{Y_D - Y_i}{X_D - X_i}\right). \tag{6}$$

Since arctan is an odd function, we finally derive the decision rule below.

$$\tan\left(\phi_{i\to k} + \theta_{i\to k}/2\right) \underset{min\theta\ =\ \angle Djk}{\overset{min\theta\ =\ \angle C'jk}{\lessgtr}} \frac{Y_j - Y_i + r\sin(\phi_{j\to k} + \theta_{j\to k}/2)}{X_j - X_i + r\cos(\phi_{j\to k} + \theta_{j\to k}/2)} \tag{7}$$

where all of the elements are given before adapting this decision rule. Thus, we can identify the left point, which composes the minimum angle, from the left two points by (7). To compute the second minimum angle, we can derive the second decision rule in the same way.

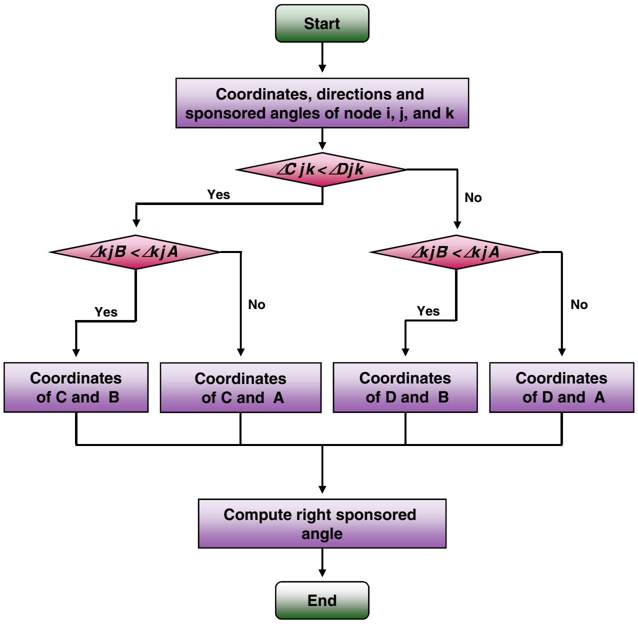


Fig. 3. Flow chart of CADA

$$\angle kjB' \underset{min\theta\ =\ \angle kjA}{\overset{min\theta\ =\ \angle kjB'}{\lessgtr}} \angle kjA \tag{8}$$

where $\angle kjB'$ and $\angle kjA$ are the right two angels in Fig. 2.

$$\tan\left(\phi_{i\to k} - \theta_{i\to k}/2\right) \underset{min\theta\ =\ \angle kjA}{\overset{min\theta\ =\ \angle kjB'}{\lessgtr}} \frac{Y_j - Y_i + r\sin(\phi_{j\to k} - \theta_{j\to k}/2)}{X_j - X_i + r\cos(\phi_{j\to k} - \theta_{j\to k}/2)} \tag{9}$$

where all of the elements are also given before adapting this decision rule. Thus, we can choose the right point, which compose the minimum angle, from the right two points by (9). By two decision rules, namely (7) and (9), we can finally compute the left and right points which compose the minimum sponsored angle.

D. Central Angle Decision Algorithm (CADA)

As shown in Fig. 3, CADA starts from the given coordinates of node i, j, and k. Directions such as $\phi_{i\to k}$ and $\phi_{j\to k}$ can be calculate by (1). Sponsored angles such as $\theta_{i\to k}$ and $\theta_{j\to k}$ can also be calculated by (2). From all given information, the first proposed decision rule (7) determines one of two left points, then second proposed decision rule (9) determines one of two right points. From the determined two points, we can obtain the right sponsored angle without any coverage-hole by the equation below.

$$\theta_{left\_pt\to j\to right\_pt} = \arctan\left(\frac{Y_{left\_pt} - Y_j}{X_{left\_pt} - X_j} - \frac{Y_{right\_pt} - Y_j}{X_{right\_pt} - X_j}\right) \tag{10}$$

where $\theta_{left\_pt\rightarrow j\rightarrow right\_pt}$ is the right sponsored central ang and X_j and Y_j denote coordinates for sensor j and $X_{left\_}$ Y_{left_pt}, Y_{right_pt}, and X_{right_pt} denote coordinates for l point determined by (7) and right point determined by (respectively.

III. NETWORK MODEL AND RADIO MODEL

In this section, we provide our simulation environments. the first part of this section, we describe the network mod The second part presents the radio model.

A. Network Model

We assume the same network model used in [7]. A fixed I is located far away from the sensor nodes. All sensor nod in the network are immobile, homogeneous, and deployed a flat area (2-Dimension). In addition, all sensor nodes c directly communicate with the fixed BS. Finally, each no controls power so that it expends the minimum required ener to transmit data to its destination.

B. Radio Model

We assume the same model used in [6][7]. In a transmitt and receiver, radio expands energy for transferring and receiving k-bit with the distance of d meter is given in (11) and (12) respectively.

$$E_{T_x}(k,d) = E_{T_x}k + E_{amp}(k,d) \tag{11}$$

where $E_{T_x}(k,d)$ denotes the total energy dissipated at the transmitter with k bits and d distance, E_{T_x} denotes per bit energy dissipations for transmission, and $E_{amp}(d)$ denotes the energy required by the amplifier for an acceptable signal-to-noise ratio.

$$E_{R_x}(k) = E_{R_x}k \tag{12}$$

where $E_{R_x}k$ denotes the energy dissipated at the receiver and E_{R_x} denotes per bit energy dissipations for reception. We use both the free-space propagation model and the two-ray ground propagation model for the path loss in wireless channel transmission. With d_o which denotes the threshold of transmission distance, the free-space model is employed where $d \le d_o$ and the two-ray model is employed where $d > d_o$. $E_{amp}(d)$ which denotes required energy by an amplifier is defined as

$$E_{amp}(d) = \begin{cases} \varepsilon_{FS} * d^2, & d \le d_o \\ \varepsilon_{TR} * d^4, & d > d_o \end{cases} \tag{13}$$

where ε_{FS} and ε_{TR} denote amplifier parameters for the free-space and the two-ray models, respectively, and d_o is the threshold distance given by

$$d_o = \sqrt{\varepsilon_{FS}/\varepsilon_{TR}} \tag{14}$$

We assume the same parameters used in [7] for our simulation: $E_{T_x} = E_{R_x} = 50nJ/bit$, $\varepsilon_{FS} = 10pJ/b/m^2$, $\varepsilon_{T_x} = 0.0013pJ/b/m^4$, $d_o = 87m$, and the energy cost for data aggregation is set as $E_{DA} = 5nJ/b/message$. Other detailed simulation parameters will be provided in Section IV.

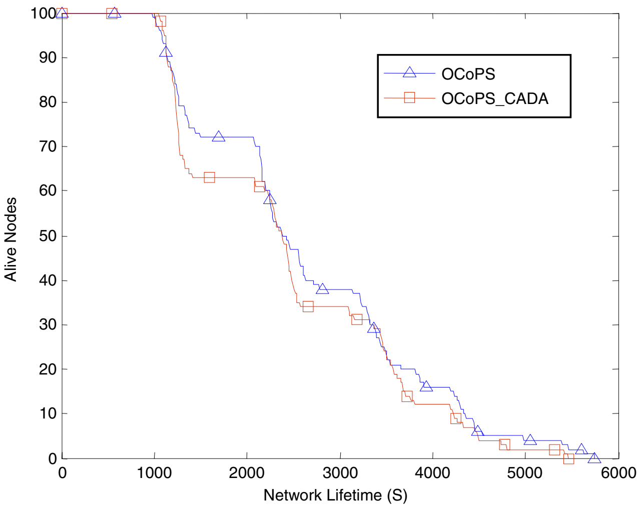


Fig. 4. Alive nodes as network lifetime function

IV. PERFORMANCE EVALUATION

In this section, we define the network lifetime and coverage rate and also present simulation results performed on Network Simulator NS-2 [8] concerning the network lifetime and network coverage rate. The purpose of this simulation is to evaluate applicability of our proposed algorithm to routing protocols and to confirm the expected improvement of network coverage at the expense of decrement of the network lifetime, ultimately derived from waking more nodes initially. For the simulation, we devise an extension of the OCoPS routing protocol with proposed CADA named as the optimal coverage-preserving scheme with the coverage angle decision algorithm (OCoPS_CADA) and compare the OCoPS_CADA with OCoPS. In the simulation, we assume the same scenario used in the OCoPS routing protocol [7]. 100 nodes are uniformly distributed in $50m \times 50m$ area. Each sensor has initial energy of 2J and the sensing range of 10 meters and knows its geographical location. Each sensor sends 2000-bit message to BS. To evaluate the coverage rates of two routing protocols, the target area is divided into $1m \times 1m$ and the $2601(51 \times 51)$ cross points detect that they are in the sensing range of on-duty nodes every 0.5 second.

A. The Network Lifetime

Fig. 4 shows the overall network lifetime for the two routing protocols. We define network lifetime as the overall time range during which at least a sensor node in a network has the ability to monitor its environment [7]. Compared to OCoPS, our simulation results show that OCoPS_CADA degrades the network lifetime nearly 5%. This is because the number of on-duty nodes in OCoPS_CADA is 37 at the beginning while the number in OCoPS is 28. OCoPS_CADA wakes more 9 nodes in order to improve the network coverage. It is noteworthy that the curves of the network lifetime, visible in Fig. 4, are shaped approximately like steps. There are two reasons for this: cluster heads (CHs) random selection used in LEACH

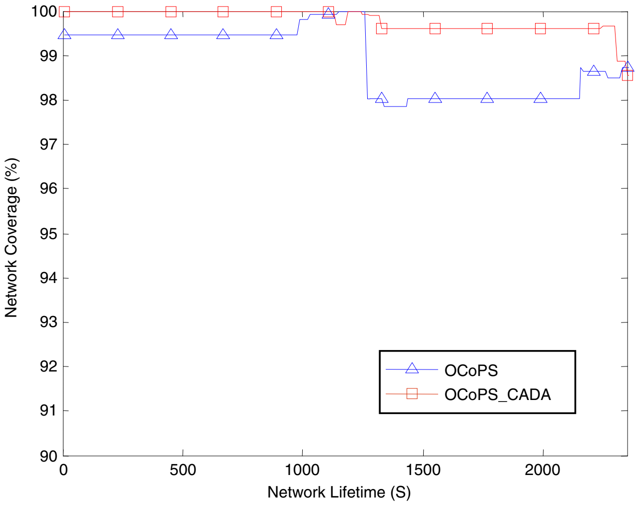


Fig. 5. Network coverage as network lifetime function

and the off-duty replacement by the wake-up strategy [7]. Since both routing protocols are extensions of the LEACH protocol and use the random selection of CH like the LEACH protocol [6], each on-duty node has the same chance to be a CH. In LEACH, the network has a steady phase and by the load balancing, nodes start to die simultaneously after a certain time. By coverage-preserving scheme and wake-up strategy, OCoPS and OCoPS_CADA replace dead nodes with off-duty nodes. After all the dead nodes are replaced, both have another steady phase. This replacement and steady phase cycle is repeated until there are no replaceable nodes.

B. The Network Coverage Rate

Fig. 5 shows the network coverage rate of two protocols. We define coverage rate as what percentile of target area (50×50) is covered by on-duty nodes. Compared to OCoPS, our simulation results show that OCoPS_CADA initially guarantees 100% of the network coverage while OCoPS covers approximately 99% of the network coverage containing 14 coverage-holes out of 2061 cross points. This is because OCoPS_CADA wakes more 9 nodes in order to guarantee 100% of the network coverage. Waking more nodes bring about 5% of the overall network lifetime decrement as shown in Fig. 4. This demonstrates the trade-off between the network coverage rate and network lifetime.

V. CONCLUSION

In this paper, we propose CADA, which definitely solves the central angle decision problem to guarantee no coverage-hole. To evaluate applicability of our proposed algorithm to routing protocols and to confirm the expected improvement of network coverage, we extend the OCoPS routing protocol with the CADA, named as OCoPS_CADA. By solving the central angle decision problem, OCoPS_CADA guarantees 100% of the network coverage at the expense of 5% decrement of the network lifetime, ultimately derived from waking more nodes initially and affordable in stringent applications such as battlefield surveillance, fire detection, toxic liquid leaking detection, and so on. It is noteworthy that as the network size becomes larger and the number of deployed nodes increases, the possibility of coverage-hole existence becomes higher. Subsequently, the coverage-holes jeopardize the overall quality of the network coverage and the derived event detection delays from the coverage-holes can cause the greater damage for target applications. Therefore, guaranteeing no coverage-hole in target applications becomes more important. For the future work, it is important to investigate that as the size of a network becomes bigger, how the proposed decision algorithm improves coverage quality in the network.

ACKNOWLEDGMENT

This work was supported by the Center for Distributed Sensor Network at GIST.

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