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Research Article

A Vector Algebraic Algorithm for Coverage Compensation in Hybrid Wireless Sensor Networks

Ning-ning Qin,[1,2] Li-xia Guo,[1] Zhi-guo Ding,[2,3] and Bao-guo Xu[1,2]

[1] *Key Laboratory of Advanced Process Control for Light Industry, Jiangnan University, Wuxi 214122, China*
[2] *The Engineering Research Center of IOT Technical Application, School of IoT Engineering, Jiangnan University, Wuxi 214122, China*
[3] *School of Electrical, Electronic and Computer Engineering, Newcastle University, Newcastle, UK*

Correspondence should be addressed to Ning-ning Qin; ningning801108@163.com

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In wireless sensor networks, coverage holes are caused by energy depletion at some nodes, and the aim of this paper is to study how to utilize the redundant nodes with remaining energy. Particularly, this paper proposes a vector algebra based algorithm by exploring redundant nodes as an extra dimension for coverage compensation. This algorithm consists of two parts. One is to find the locations of potential redundant nodes for coverage compensation; and the other is to opportunistically select the best redundant nodes by jointly considering the hole boundaries and the remaining energy of nodes. Simulation results are provided to demonstrate that the proposed algorithm minimizes the energy consumption when repairing the holes for full coverage. Furthermore, compared with other algorithms, the proposed one exhibits better performance in terms of moving distance and energy consumption.

1. Introduction

Wireless sensor networks (WSNs) are composed of numerous small-size sensors that have various features, such as low cost, light weight, high mobility, and capabilities for sensing, computing, and communications. The sensor has the same capabilities as the machine does. In fact, WSNs are one of typical application of machine to machine communications. The "smart home" is just an example. It is not only a good application based on WSN but also an instance of machine to machine communications. With these features, WSNs have been widely used in many fields, including intelligent transportation, military applications, infrastructure monitoring, antiterrorism disaster relief, environmental monitoring, wireless healthcare, and target tracking [1–3].

Coverage is an important metric of the quality of service (QoS) in WSNs [4, 5] and is a fundamental issue since each sensor is energy constrained. The reason why some areas are not covered is due to random deployment of sensors, node energy depletion, or environmental damages. Consequently, coverage holes appear in various parts of WSNs [6, 7], significantly reducing the QoS and the lifetime of the network. An important observation is that a number of inactive redundant nodes also exist in the network, which results in the simultaneous coexistence of two types of sensors, one with extra energy and the other with drained batteries. In hybrid WSNs, such a difficulty can be overcome by moving mobile redundant sensors to the locations at which coverage holes occur.

Many recent studies on patching holes by exploring mobile nodes are based on geometry. Reference [8] proposed the Coverage Hole Patching Algorithm (CHPA), which selects the patching point along the perpendicular bisector between any two adjacent hole boundary nodes. The distances between the selected point and the corresponding two boundary nodes are equal to the communication radius. This algorithm can be easily implemented due to its low complexity but suffers low resource efficiency. To overcome this shortcoming, the two-point vertical determination method was modified to a three-point approach in the Patching Algorithm Triangle by Triangle based on mobile node (PATT) [9]. Compared with CHPA, PATT can achieve better stability and higher coverage but does not consider the use of the existing redundant sensors. Reference [10] proposed the use of a vector algebra distributed method to achieve effective deployment of redundant nodes. This algorithm effectively uses the existing redundant resources while maintaining a sufficient level of coverage. However, [10] did not consider the energy consumption caused by long-distance moving.

In order to use such redundant node resources, this paper proposes a novel mobile node scheduling algorithm, namely, a Dispatching Algorithm based on vector algebra at mobile node (DAVM), for patching holes in hybrid WSNs. Localization algorithms are independently carried out at both static and mobile nodes. Particularly, the first step of the proposed algorithm is to find where patching position is. Then the mobile sensors adjacent to boundaries calculate their moving distance and direction towards the patching position. Static nodes will select their best patching redundant nodes individually. The criterion for node selection is based on the largest remaining energy which is determined by moving distance and initial energy of redundant node. At last, the selected nodes will be activated and asked to move towards the patching positions. Those nodes are not utilized before they are activated. DAVM provides an effective method to utilize redundant nodes. It is worthy pointing out that redundant nodes calculate their corresponding patching positions by using the local and one-hop positioning information. And the proposed node scheduling method can not only avoid patching conflict caused by more than one redundant node nearby the boundaries but also minimize the energy consumption caused by node moving by inviting the nodes close to the boundaries. Simulation results are provided to demonstrate the superior performance of the proposed scheduling algorithm by comparing it with some existing schemes.

2. Preliminaries

2.1. Network Model. Consider a hybrid wireless sensor network which consists of randomly deployed n sensor nodes. These sensors comprise a set C, including both static nodes and mobile redundant nodes. Static nodes do not have energy harvesting ability, whereas mobile redundant nodes cannot move and sense until they are activated. Mobile redundant nodes have the same capacities as static nodes in terms of communication, sensing, and data processing. Moreover, mobile redundant nodes can have thea priori information about their own initial energy. The binary perception model is adopted at all of the nodes [11]. According to [12–14], the communication radius (R_c) is assumed to be twice the coverage radius (R_s) in order to obtain a connected network. Each node $u(x_u, y_u)$ can obtain the relative positions of adjacent nodes by using its directional antenna and algorithms in [15, 16]. The probability that the sensing discs of any three sensors would intersect at a single point is close to zero because of the random deployment of the nodes. No more than one sensor is located at the same point. And every sensor node should have at least two neighbors to avoid the isolated coverage or teardrop shaped coverage. In addition, the location information of the sink node is known to all other nodes.

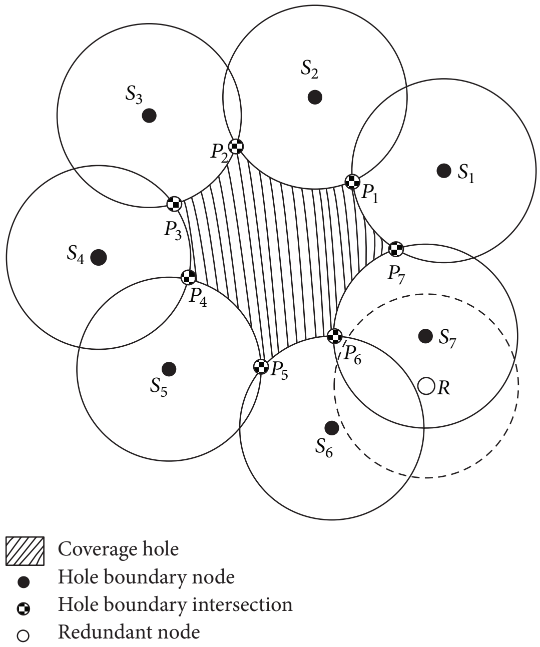


Figure 1: Coverage holes.

We assume that the coverage holes are closed and inside the monitoring region. We can obtain all the information about the boundary nodes of the coverage hole by using hole detection algorithm [17]. In [17], the maximum simple complex is built according to network topology. When a node is adjacent to the edges of the maximum simple complex network, this node is a hole boundary node but not vice versa.

2.2. Relative Definitions

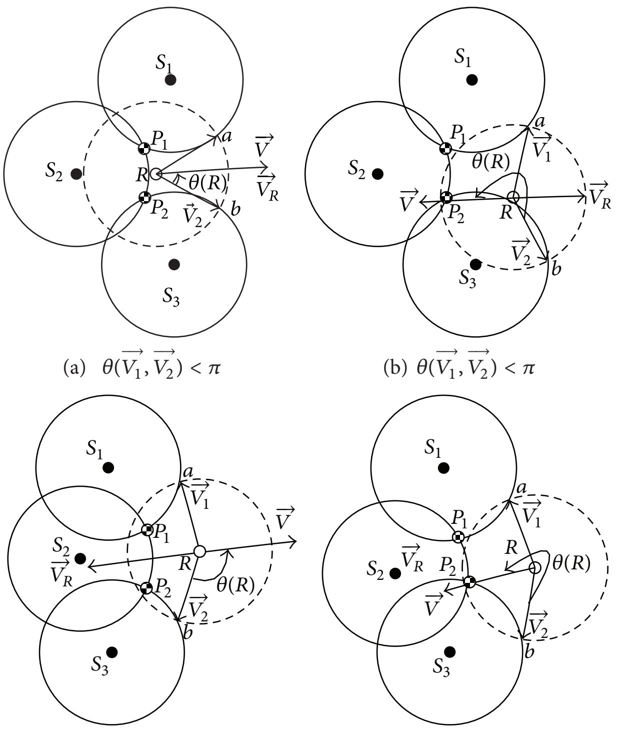
Definition 1 (coverage hole). If a continuous area is not covered by any sensor node in WSNs, this area is defined as a coverage hole [19]. As shown in Figure 1, the shadow area is a coverage hole. Given a set of boundary nodes $S = \{S_i \mid i = 1, 2, \ldots, \text{Num}\}$, where $S \subset C$, $S_i \in S$ is a hole boundary node.

Definition 2 (hole boundary neighbor). The two nodes $S_i, S_j \in S$ are mutually hole boundary neighbors if $d(S_i, S_j) \leq R_c$ where $d(\cdot)$ is the 2D Euclidean distance between the two nodes.

Definition 3 (hole boundary intersection). If two hole boundary nodes intersect at one point within a hole that is beyond the scope of the third node's sensing range, then this intersection point is called a hole boundary intersection.

3. Vector Algebra Principles

The fundamental function of DAVM is to calculate the potential patching locations. In consideration of the existing coverage hole, vector algebra can be used to move the



(a) $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) < \pi$

(b) $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) < \pi$

(c) $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) > \pi$

(d) $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) > \pi$

Figure 2: Mobility azimuth of R.

redundant nodes. Without any constraints, more than one redundant node can patch the hole. Therefore, choosing the best node is another challenging problem considered in DAVM. To be considered effective, DAVM needs to guarantee that the patching node covers the hole without splitting the hole; that is, the patching node does not generate new holes [20, 21].

Thus, DAVM consists of two parts: (1) calculating the displacement of the redundant node, including the direction and the distance; and (2) identifying the hole boundary node and scheduling the best redundant node.

3.1. Displacement of Redundant Node

(i) Moving Direction. Consider a part of hole boundary that includes S_1 and its neighbors S_2 and S_3, as illustrated in the following example. Given a redundant node $R(x_R, y_R)$, their sensing circles of $R(x_R, y_R)$ intersect with S_1 and S_3 at $a(x_a, y_a)$ and $b(x_b, y_b)$ as shown in Figure 2. The following can be calculated:

$$\overrightarrow{V_1} = (x_a - x_R)\vec{i} + (y_a - y_R)\vec{j},$$
$$\overrightarrow{V_2} = (x_b - x_R)\vec{i} + (y_b - y_R)\vec{j}, \qquad (1)$$
$$\overrightarrow{V_R} = \overrightarrow{V_1} + \overrightarrow{V_2},$$

where $\theta(\vec{i}, \vec{j})$ is defined as the mobility azimuth that is counterclockwise from $\vec{i}$ to $\vec{j}$. If V_2 is regarded as the reference vector, the mobility azimuth of R is defined as $-\theta(\overrightarrow{V_2}, R)$ or simply as $\theta(R)$. Let the auxiliary vector $\overrightarrow{V}$ satisfy $\theta(R) = \theta(\overrightarrow{V})$ and $\| \overrightarrow{V} \| = \| \overrightarrow{V_R} \|$. The following four cases are considered for the calculation of $\overrightarrow{V}$, as shown in Figures 2(a)–2(d). Then, $\theta(R)$ is obtained.

Case 1. When $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) < \pi$, $\forall P_k$, if $d(R, P_k) \le R_s$, there is $\overrightarrow{V} = \overrightarrow{V_R}$.

Case 2. When $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) < \pi$, $\exists P_k$, if $d(R, P_k) > R_s$, there is $\overrightarrow{V} = -\overrightarrow{V_R}$.

Case 3. When $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) > \pi$, $\forall P_k$, if $d(R, P_k) \le R_s$, there is $\overrightarrow{V} = -\overrightarrow{V_R}$.

Case 4. When $\theta(\overrightarrow{V_1}, \overrightarrow{V_2}) > \pi$, $\exists P_k$, if $d(R, P_k) > R_s$, there is $\overrightarrow{V} = \overrightarrow{V_R}$.

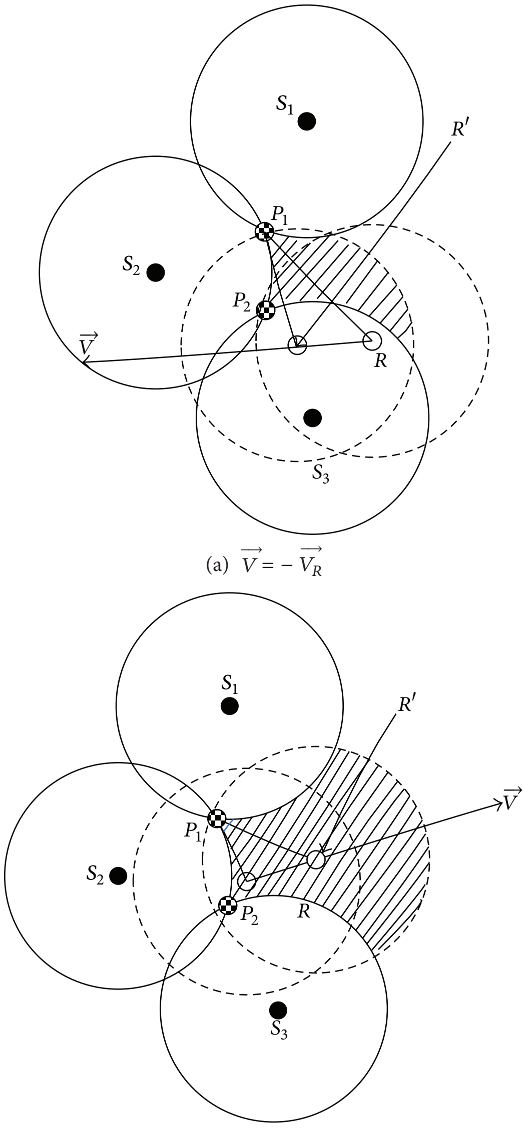
(ii) Moving Distance. The moving distance of R, L_0 is dependent on both R and hole boundary intersections. As shown in Figure 3, the hole boundary node S_2 exists; its sensing range intersects the ranges of S_1 and S_3 at $P_1(x_{P_1}, y_{P_1})$ and $P_2(x_{P_2}, y_{P_2})$, respectively. The calculation flow of L_0 is shown as follows:

$$\overrightarrow{V_{RP_k}} = \left(x_{P_k} - x_R\right)\vec{i} + \left(y_{P_k} - y_R\right)\vec{j},$$
$$\cos\theta\left(\overrightarrow{V_{RP_k}}, \overrightarrow{V}\right) = \frac{\overrightarrow{V_{RP_k}} \bullet \overrightarrow{V}}{\left|\overrightarrow{V_{RP_k}}\right| \times \left|\overrightarrow{V}\right|},$$
$$L_0 = L_{RP_k} \times \cos\theta\left(\overrightarrow{V_{RP_k}}, \overrightarrow{V}\right) + \sqrt{{R_s}^2 - {L_{RP_k}}^2 + {L_{RP_k}}^2 \cos^2\theta\left(\overrightarrow{V_{RP_k}}, \overrightarrow{V}\right)}, \quad \text{where}$$
$$L_{RP_k} = \sqrt{\left(x_R - x_{P_k}\right)^2 + \left(y_R - y_{P_k}\right)^2}. \qquad (2)$$

The new position R' can be determined by using $\theta(R)$ and L_0. Two new positions are calculated by P_1 and P_2. An R' that satisfies $d(R', P_k) \le R_s$ $(k \in [1, 2])$ is chosen as the new position. Therefore, the moving distance should be calculated by the chosen R'.

3.2. Best Redundant Node. More than one node may try to participate into patching because of the high mobility of redundant nodes. To avoid patching collision, the best redundant node should be selected in terms of energy and moving distance. Thus, the evaluated remaining energy $E_r(i)$ of the redundant node R_i can be calculated as follows:

$$E_r(i) = \alpha E_0(i) - \beta L_0(i), \qquad (3)$$



(a) $\overrightarrow{V} = -\overrightarrow{V_R}$

(b) $\overrightarrow{V} = \overrightarrow{V_R}$

Figure 3: Moving distance based on the new position R'.

where $E_0(i)$ is initial energy of node i, $\alpha (\alpha \geq 1)$ is the energy endurance parameter; β is the consumption of energy per unit distance, that is, the energy consumption parameter, which is governed by the given work environment and the physical properties of the nodes.

Let E_{th} be the threshold energy required for working. The best moving node R_{best} can be selected if $E_r(R_{\text{best}})$ is larger than both E_{th} and that of the other nodes.

4. DAVM

In DAVM, the hole boundary node S_j broadcasts the information regarding the hole. Any redundant node R_i that receives this message runs the displacement algorithm and replies to S_j. Then, S_j activates the best redundant node R_{best} by using the feedback messages from the redundant nodes. And node R_{best} moves to a new location. Let the queue Q_{all} record the displacements and energy information of the redundant nodes. The procedures of the displacement algorithm and the best redundant node schedule are presented in detail in the following sections.

4.1. Displacement Algorithm. When a redundant node R_i receives the information on the hole, the following steps are carried out.

Step 1. Calculate $L_0(i)$, $\theta(i)$, and $E_r(i)$.

Step 2. Reply $L_0(i)$, $\theta(i)$, $E_0(i)$, and $E_r(i)$ to S_j.

Step 3. Start the timer T.

Step 4. If T is out of time, proceed to Step 6.

Step 5. If R_i receives the activated command from S_j, it will be activated and move to the new position based on $(\theta(i), L_0(i))$; otherwise, proceed to Step 4.

Step 6. Enter a dormancy state.

4.2. Best Redundant Node Schedule. The hole boundary node S_j runs the following.

Step 1. Calculate the value of $\theta(\overrightarrow{V_{S_jS_k}}, \overrightarrow{V_{S_jS_i}})$, where S_i is the right hole boundary neighbor and S_k is the left one. If $\theta(\overrightarrow{V_{S_jS_k}}, \overrightarrow{V_{S_jS_i}}) < \pi$, proceed to Step 2; otherwise, select the next hole boundary node counterclockwise until the selected node S_j satisfies $\theta(\overrightarrow{V_{S_jS_k}}, \overrightarrow{V_{S_jS_i}}) < \pi$.

Step 2. S_j broadcasts the hole information.

Step 3. Wait for the feedback messages from the redundant nodes and update Q_{all}.

Step 4. Based on Q_{all}, S_j selects the best redundant node R_{best}.

Step 5. Send activated command to R_{best}.

Step 6. Update the set S.

4.3. DAVM for Multiple Holes. In applications, it is a fact that there is more than one hole in WSN because of random deployment. If these holes are separated and satisfy the network model in Section 2.1, DAVM can still work effectively through patching them one by one. It is not overlooked that the patching order of holes might affect the results of DAVM. That is, the set of nodes used for holes patching may not be the same if the holes are patched in different orders. But the local optimality can be obtained when patching multiple holes in sequence, because DAVM can select the best redundant node from the remaining redundant node.

Table 1: Simulation parameters and calculations.

Parameters	Calculation description
Coverage hole region	A N-polygon about 12 meters on a side, where $N \in [6, 29]$
Area of hole S	$36N/\tan(\pi/N)$ (m^2)
Hole-boundary node number	N
Redundant node number M	$144N/\pi R_s{}^2 \tan(\pi/N)$
Initial energy $E_0(i)$ of redundant node i	$E_0(i) \in [90, 110]$ (J)
Communication radius R_c	16 m
Coverage radius R_s	8 m
Energy endurance parameter α	1 (network without endurance ability)
Energy consumption parameter β [18]	1 J/m
Energy threshold E_{th}	60 J

5. Simulation

5.1. Simulation Environment. The simulations are implemented by using Matlab. DAVM is evaluated and compared with the coverage optimization algorithm (COA) mentioned in [10]. Note that COA is also based on vector algebra. In consideration of the randomness in WSNs, the simulation is performed 20 times with the same topology for each algorithm in each scenario according to Monte Carlo theory. The simulation focuses on a normal N-polygon hole, and the N vertices are the N hole boundary nodes. The length of the edge is constant; thus, more N corresponds to a larger hole. For the multiple holes, DAVM can be usedpatching these holes one by one.

Furthermore, the initial energies and positions of the redundant nodes are random in the coverage hole. The simulation parameters and calculations are given in Table 1.

5.2. Simulation Analysis

5.2.1. Coverage Evaluation. The coverage ratio is the ratio of the covered area to the area of hole. Figure 4 shows the relationship between the coverage ratio and the number of mobile nodes Sum in different N-polygon holes, where $N \in [17, 29]$. After running DAVM, the coverage ratio approximately increases linearly with an increasing number of mobile redundant nodes. Repeated experiments reveal that the increasing trend slows down with the enlarging hole using linear fitting method. Let the line slope K be the trend, in which the coverage varies with the number of mobile nodes; obviously, $K \geq 0$. In the experiment, the number of edges of hole N increases from 17 to 29, but K decreases from 0.0551 to 0.0178. Thus, for a larger area of the hole, the coverage gain of additional nodes is not significant, because more additional nodes are needed to compensate the larger coverage losses.

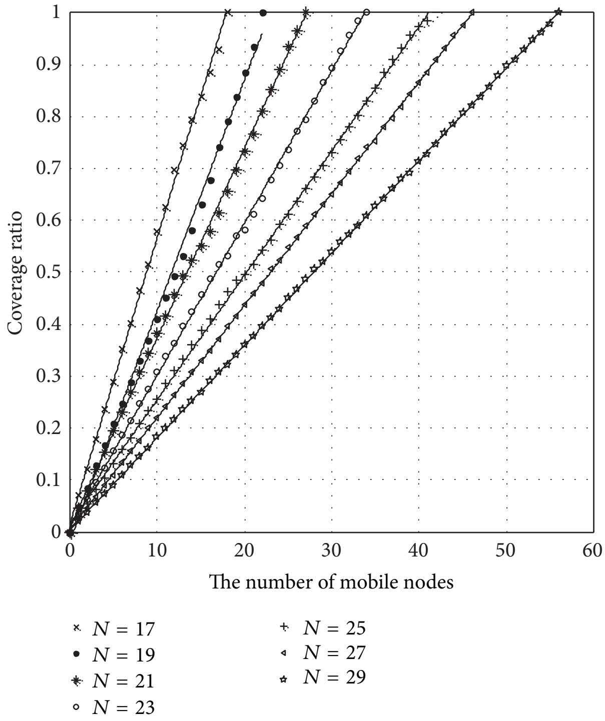


Figure 4: Number of mobile nodes versus coverage ratio.

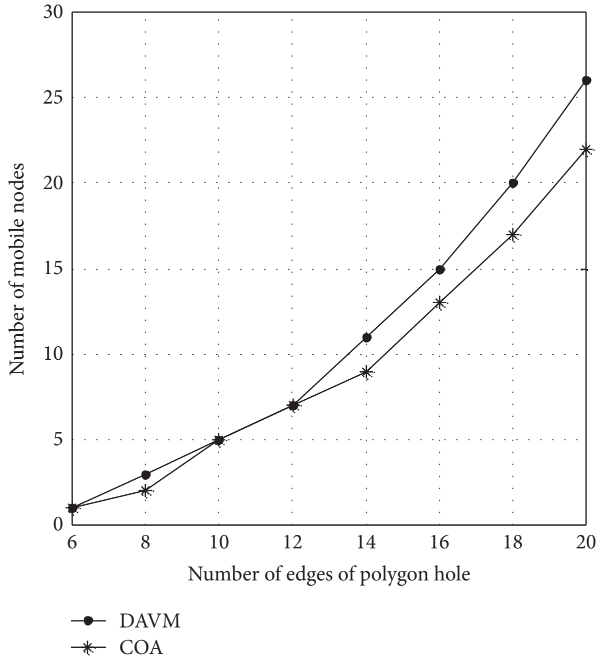


Figure 5: Evaluation on number of mobile nodes.

5.2.2. Evaluation of the Total Number of Mobile Nodes. As shown in Figure 5, the number of activated redundant mobile nodes is simulated for various hole sizes. The number of redundant mobile nodes activated Sum increases with an enlarging hole in both algorithms. Compared with DAVM, COA requires smaller mobile nodes for a larger hole ($N >$

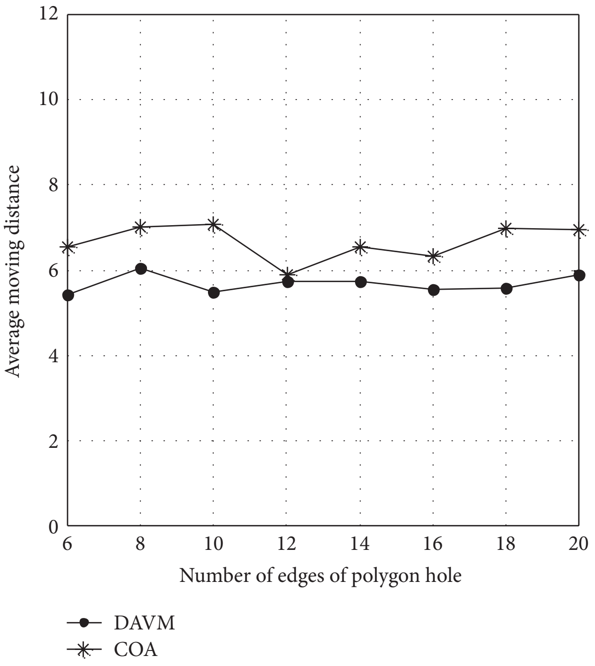


Figure 6: Evaluation on average moving distance L.

12), which is due to the fact that COA can only guarantee 90% coverage. On the other hand, DAVM is to achieve approximately 100% coverage but requires the activation of more mobile nodes. Or in other words, DAVM can provide a better performance than COA in terms of hole compensation with a price of more system complexity.

5.2.3. Evaluation of Average Moving Distance. The moving distance of the mobile node directly affects the energy consumption. To analyze the average moving distance, several algorithms are simulated to evaluate the energy consumption in different holes. The average moving distance L is defined as follows:

$$L = \frac{1}{\text{Sum}} \sum_{i=1}^{\text{Sum}} L_0 \left(R_{\text{best},i}\right). \tag{4}$$

As shown in Figure 6, the average moving distance L shows an obvious pulsation when the area of the hole increases (i.e., $N \uparrow$) because COA does not consider the remaining energy of nodes. In DAVM, L stably ranges from 5 to 6, which is smaller than the range from 6 to 8 in COA. This finding verifies that the best redundant node schedule balances the energy.

5.2.4. Evaluation of Average Remaining Energy. Figure 7 shows the average remaining energy with the hole size N and β. The average remaining energy E is defined as follows:

$$E = \frac{1}{\text{Sum}} \sum_{i=1}^{\text{Sum}} E_r \left(R_{\text{best},i}\right). \tag{5}$$

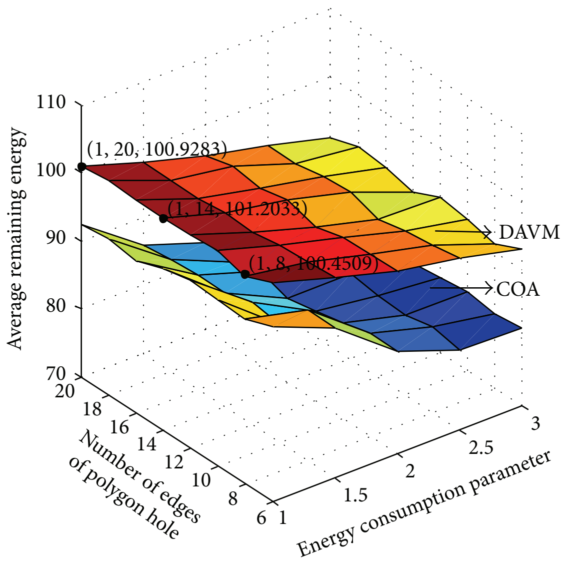


Figure 7: Evaluation of average remaining energy E, where coordinates (X, Y, Z) refer to β, N, and E.

DAVM takes the remaining energy of nodes into the consideration when designing the scheduler, which is important to effectively prevent larger moving distances of nodes and hence avoid consuming excess energy. As shown in Figure 7, the average remaining energies of both algorithms fluctuate minimally with various N and β. Compared with COA, DAVM has smoother and higher energy surface, and the fluctuation range is maintained within 1%. As result, the decrease of the network lifetime brought by using DAVM would be less than the use of COA. With an increase in β, E decreases, especially in COA. Therefore, DAVM is less sensitive to β.

5.2.5. Evaluation of Average Computation Time. The comparison of average computation time of nodes under several conditions is shown in Table 2, and Figure 8 presents the corresponding box plots. As shown in Figure 8, the computation time ranges from 0.304 s to 0.399 s for different N-polygon holes. Given a certain β, DAVM has consistently shorter computation time than COA. The performance of DAVM is more effective than COA.

6. Conclusions

This paper has proposed a novel algorithm to combat coverage holes by using redundant nodes in a wireless sensor network. The proposed algorithm achieves a balanced tradeoff between the initial energy and the moving energy consumption and chooses the best redundant node to patch the hole. Simulation results have been provided to show that DAVM is superior to COA for several aspects. However, DVAM may not be effective to the scenarios with sparse redundant nodes. A promising future direction is to focus on coverage holes with sparse redundant nodes.

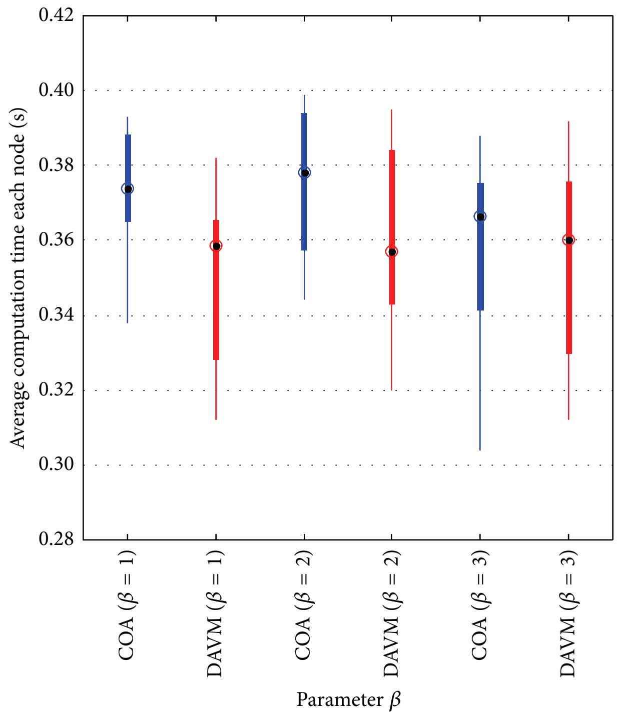


FIGURE 8: Box plots of simulation results for average computation time of each node.

TABLE 2: Average computation time of each node.

Scenario		Average computation time of each node (sec)					
#	N	DAVM			COA		
		$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 1$	$\beta = 2$	$\beta = 3$
1	6	0.393	0.376	0.367	0.382	0.367	0.329
2	8	0.376	0.344	0.379	0.312	0.378	0.364
3	10	0.388	0.380	0.304	0.369	0.347	0.360
4	12	0.372	0.395	0.372	0.356	0.395	0.392
5	14	0.338	0.367	0.366	0.361	0.346	0.360
6	16	0.368	0.348	0.388	0.327	0.320	0.388
7	18	0.363	0.393	0.336	0.329	0.340	0.330
8	20	0.390	0.399	0.347	0.362	0.391	0.312

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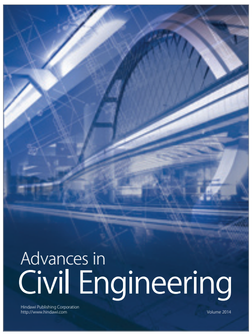
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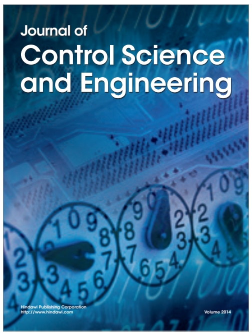
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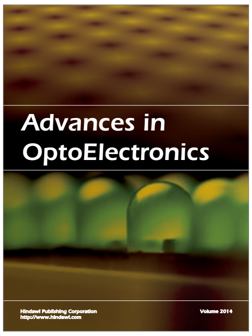
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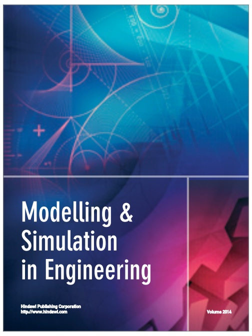
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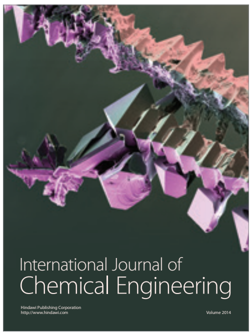
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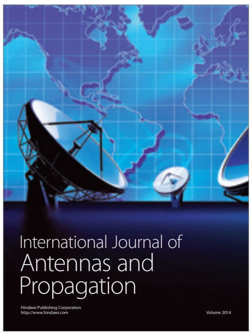
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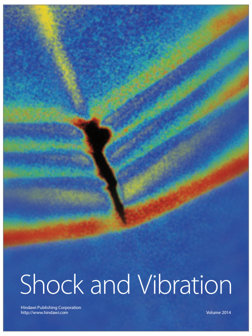
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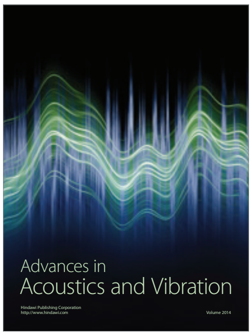
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