HORA: A Distributed Coverage Hole Repair Algorithm for Wireless Sensor Networks

Prasan Kumar Sahoo, *Member, IEEE* and Wei-Cheng Liao, *Member, IEEE*

Abstract—In wireless sensor networks, random deployment of nodes may cause serious coverage overlapping among the nodes and the original network may suffer severe coverage problems due to death of the nodes after deployment. In this paper, efficient distributed coverage hole repair algorithms are proposed taking density of the nodes in the post deployment scenario. The proposed algorithms consider limited mobility of the nodes and can select the mobile nodes based on their degree of coverage overlapping. In order to repair coverage holes of the network, nodes with higher degree of density are moved to maintain uniform network density without increasing the coverage degree of the neighbors of a mobile node. Simulation results show that the energy consumption due to mobility of nodes is least as compared to other similar protocols of the Wireless Sensor Networks. Besides, it is observed that substantial amount of coverage overlapping can be minimized and percentage of coverage of the holes can be maximized.

Index Terms—Wireless sensor networks, density control, coverage, mobility, hole repair

1 Introduction

In wireless sensor networks (WSNs), sensors are deployed randomly over a monitoring region with higher degree of density of nodes. Unfortunately, due to random deployment strategy, certain areas of the monitoring region may have coverage holes and serious coverage overlapping, which significantly degrade the network performance as mentioned in [1]. Besides, failure of electronic components, software bugs, and destructive agents could lead the random death of the nodes and also nodes may die due to exhaustion of battery power, which may cause the network uncovered and disconnected. Furthermore, sensors are normally deployed in remote or hostile environments, such as a battlefield or desert, where it is impossible to recharge or replace the battery. However, the data gathered by the sensors is generally highly critical and may be of scientific or strategic importance. Hence, coverage provided in the sensor networks is a critical criterion of its effectiveness and its maintenance is highly essential to form a robust network.

To ensure the monitoring area is fully covered, several deployment algorithms have been proposed instead of random deployment. The concept of connected dominating set proposed in [2] constructs k-connected and k-dominating sets as the backbone of WSNs to cover the monitoring area. A divide-and-conquer deployment algorithm based on the triangular form is proposed by [3]. Each triangle, calculated by three static nodes includes at least one interior angle to ensure the entire monitoring area is covered. The concept of k-angle coverage proposed in centralized and distributed polynomial-time algorithms [4] utilizes the minimum number of sensors to cover the maximum number of objects such that each object is certainly monitored by k sensors and satisfies the angle constrain simultaneously.

In addition to the coverage, connectivity between sensors is always affected by the coverage since information is hardly transferred effectively if coverage holes or severe coverage overlapping exists in the network. Therefore, an exposure-based model in [5] is proposed to measure the surveillance ability of a sensor network. It determines the maximal breach path (MBP) by Voronoi Diagram and the maximal support path (MSP) by Delaunay Triangulation to reinforce the surveillance ability. An asymptotic path-sensing with two-dimensional Boolean model is proposed in [6] to guarantee that the arbitrary path in finite networks is covered by at least k sensors.

The ratio of sensing range to communication range also can be auxiliary factor to enhance the methods based on graph theory. As mentioned in [7], the communication range (R_c) and the sensing range (R_s) of sensors can be controlled or adjusted by itself such that the coverage and connectivity can be guaranteed. The authors in [8] discuss the relation between connectivity and k_s-coverage with $2R_s \leq R_c$, where they use the concept to satisfy different demands of coverage degree with smallest set of nodes. In order to maximize the network lifetime, heuristic algorithms with network flow are proposed in [9], which find several disjoint sets to maintain the coverage and connectivity without any restriction of sensing or transmission range. In [10], all sensors are divided into several clusters based on the spatial density and duty-cycles of the sensors such that k-coverage and connectivity can be achieved among all active nodes with various ratio of R_c to R_s. A cluster method based on density of nodes is proposed in [11] without considering specific sensing and communication range.

WSNs cannot work efficiently if serious coverage overlapping due to redundant nodes is present. Hence, designing an optimal node deployment strategy to static nodes is

- *P.K. Sahoo is with the Department of Computer Science and Information Engineering, Chang Gung University, Guishan 333, Taiwan, R.O.C. E-mail: pksahoo@mail.cgu.edu.tw.*
- *W.-C. Liao is with CAMEO, Taipei 114, Taiwan, R.O.C. E-mail: weichengliao@hotmail.com.*

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another issue of density control in WSNs, which can satisfy various demands of coverage and connectivity. In [12], authors investigate the influence of optimum node density with finite number of nodes with infinite area and node numbers. An asymptotically optimal deployment pattern is proposed in [13] to achieve four-connectivity and full coverage with variable coverage and communication ranges. A redundant elimination algorithm based on Voronoi diagram is proposed in [14]. The authors design several optimal patterns in [15], which evolve from lattice deployment to guarantee k-connectivity and full coverage in 3D space without any restriction of sensing or communication range. A polygon-based methodology is proposed in [16] to reach the optimal deployment patterns for higher degree of connectivity with certain ratio of R_c to R_s. An optimal geographical density control protocol is proposed in [17], which minimizes the overlapping area between active nodes in each working set without disturbing the connectivity and coverage. Although graph theory plays a vital role to improve the coverage, there are exceptions. For instance, [18] proposes a scan-based deployment algorithm, which divides the network into mesh of clusters and then balances the load of each cluster through row and column scan.

To simplify the coverage hole recovery problem, most papers assume that the coverage holes have been detected accurately. In [19], the coverage hole is detected based on the first homology classes of the Rips complex. A probability model with several network parameters is designed in [20] to detect the coverage holes. Authors in [21] propose a fuzzy-logic based algorithm for different areas to discover the coverage holes. The concept of density control is still workable for mobile sensors which are used to minimize the overlapping area to eliminate the coverage holes or maintain the coverage and connectivity according to the density of nodes. In [22], authors present a method that determines the redundant nodes for eliminating the coverage holes in a high density network. Unfortunately, some coverage holes cannot be fully eliminated if no more redundant nodes can be moved. Authors in [23] propose the coverage and connectivity maintenance algorithms with redundant nodes, which calculate the available mobility distance before moving to recover holes. Algorithms in [24] are proposed to maintain the coverage through Voronoi diagram. They control the size of each Voronoi cell to eliminate the coverage holes. In this case, the communication range must be longer enough otherwise the Voronoi cell of each node may not be judged precisely.

In [25], authors utilize the multiplicative weighted Voronoi diagram to decide new location of the mobile sensor in its Voronoi cell. However, big coverage holes can be formed in the network, if numbers of deployed nodes are insufficient. Though a relative neighborhood graph based connectivity maintenance algorithm [26] is proposed with moving distance of the mobile nodes, the vector-based coverage algorithm cannot guarantee the minimization of overlapping area. As proposed in [27], the density control is converted into the flow control problem for deciding the maximum mobile distance. Though, the protocol promises k-coverage with mobile nodes, it does not consider the case of minimizing overlapping area. The authors in [28] analyze the asymptotic coverage under uniform deployment scheme with random walk mobility model. In terms of dynamic k-coverage under the Poisson deployment scheme with random walk mobility model, it studies how coverage varies based on the relation between coverage and the sensing range. However, it does not consider the case of minimizing coverage overlapping.

Due to random deployment of nodes, uniform distribution of density of the nodes cannot be guaranteed. Besides, maintenance of the network coverage and connectivity is highly essential as a small un-monitored area can spoil the whole purpose of the network if it goes undetected. From the survey of current literature, though different coverage and connectivity maintenance algorithms are found, to the best of our knowledge, none of the work proposes how to maximize the recovery of coverage holes by minimizing the degree of coverage overlapping. Hence, we design algorithms to minimize the coverage overlapping of the network by moving nodes from the serious coverage overlapping areas and to repair the coverage holes. The main contributions of our work can be summarized as follows:

- A distributed nonlinear programming based (NLP) algorithm is proposed to minimize the coverage overlapping of the nodes due to random deployment and thereby to maintain uniform density of the network.
- Algorithms are designed to select mobile nodes based on their highest coverage degree, which can be done in an autonomous manner in any convex monitoring region by maintaining the network integrity dynamically.
- Algorithms are designed to repair multiple coverage holes of the network by using few mobile nodes without disturbing the existing coverage and connectivity of the network. In the proposed schemes, mobility of the nodes is limited within only one hop.

The rest of paper is organized as follows. Problem formulation of our protocol is introduced in Section 2. The distributed density control based hole repair algorithms (HORA) are described in Section 3. Performance evaluation of our work is done in Section 4 and concluding remarks are made in Section 5 of the paper.

2 Problem Formulation

Consider a fully covered and connected homogenous wireless sensor networks, where nodes are deployed randomly. At the time of deployment, some part of the network has higher degree of coverage whereas other parts are sparsely covered, which is obvious in random deployment. It is assumed that each sensor knows its own location and location information of its one-hop neighbors. In the post deployment stage, coverage holes are created in the network due to predicable or unpredictable death of the nodes such as battery power exhaustion or explosion. In our protocol, it is considered that the immediate one-hop neighbors of a dead node know the location of the holes in the network based on the location of the dead nodes. Throughout our work, it is considered that the communication range (R_c) is twice of the sensing range (R_s). We define few terms that are used in the following sections of our protocol.

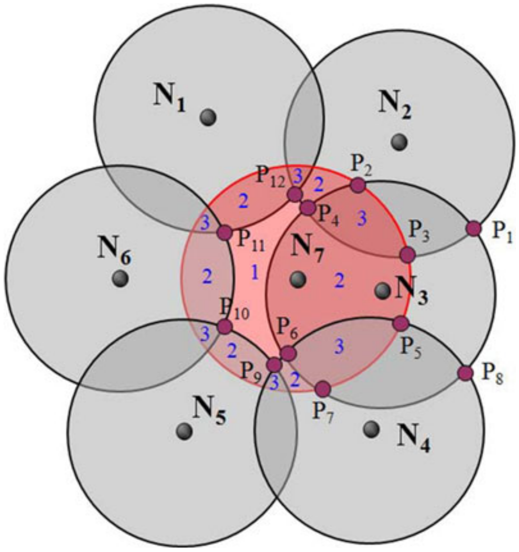

Fig. 1. Example of boundary nodes, covered points and K_h-value.

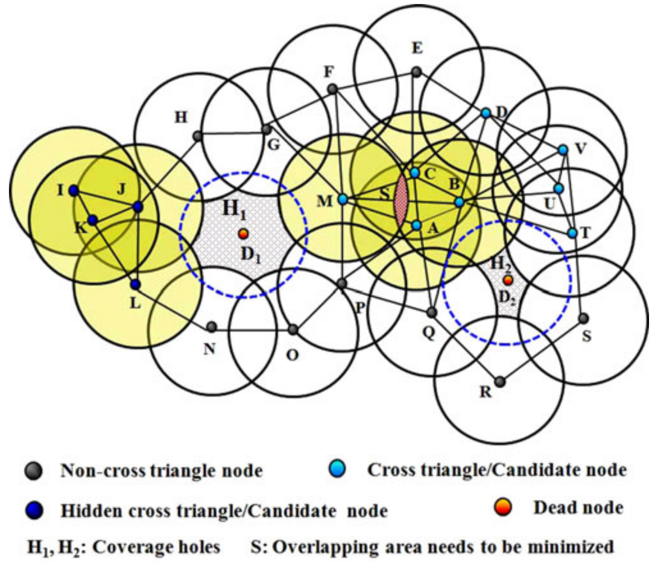

Fig. 2. The definition of *CT*, *HCT*, *NCT* node, and COR as well as selection of a mobile node for $K_h \geq 4$.

Boundary nodes. Let S_i be the one-hop neighbors of sensor S_j, $\forall\ i = 1, 2, 3, \ldots, m$, where m is the total number of S_j's one-hop neighbors and $i \neq j$. Let A be the coverage area of sensor S_j and E be the union of coverage areas induced by S_j's one-hop neighbors S_i such that $E \bigcap A \neq A$. Then, sensors S_i, $\forall\ i = 1, 2, 3, \ldots, m$ are Boundary nodes of sensor S_j, if it is dead. As shown in Fig. 1, sensors N_1 through N_6 will be Boundary nodes of sensor N_7 as they enclose the hole due to the death of node N_7.

k-cover. The *k*-cover is a value of the intersection of coverage areas induced by *k* sensors. For instance, as shown in Fig. 1, the *k*-cover of node N_7 with its neighbor N_3 is 2, whereas with both neighbors N_2 and N_3 is 3 each.

K_h-value. If a sensor S_i has m number of one-hop neighbors S_j, $\forall\ j = 1, 2, 3, \ldots, m$, and $i \neq j$ such that $k_1, k_2, k_3, \ldots, k_n$ be the all possible *k*-covers of S_i with S_j for $m \neq n$, then $K_h - value\ = \max\{k_1, k_2, k_3, \ldots, k_n\}$. For example, as shown in Fig. 1, we can find all possible *k*-covers of node N_7 with its one-hop neighbors represented by the natural numbers. Now, the highest value of these *k*-covers, which is K_h-value of sensor $N_7 = 3$.

Covered points. Let S_i be the one-hop neighbors of sensor S_j, $\forall\ i = 1, 2, 3, \ldots, m$, where m is the total number of S_j's one-hop neighbors and $i \neq j$. If P_k represents the points of intersection of coverage area of sensor S_j with coverage area of its one-hop neighbors S_i, $\forall\ k = 1, 2, 3, \ldots, n$, where n is the total number of covered points, such that all $P_k \in S_j$, then each P_k is a Covered point of sensor S_j. As shown in Fig. 1, coverage area of N_3 intersects with coverage area of its one-hop neighbors N_2, N_4 and N_7 such that points of intersection P_1 through P_8 lie on or within the coverage area of N_3. Hence, points P_1 through P_8 are called *Covered points* of sensor N_3.

Cross triangle (CT) and hidden cross triangle (HCT) nodes. Let $G = (V, E)$ be a complete graph of order k, where vertex V represents location of a node and edge E represents communication link between any two nodes of the network. The nodes who can form such a complete graph of order k, $\forall\ k \geq 4$ are called Cross Triangle nodes. If locations of at least any three Cross Triangle nodes of such complete graph of order k, $\forall\ k \geq 4$ are collinear, the nodes who form such a graph are called Hidden Cross Triangle nodes. As shown in Fig. 2, nodes M, A, B, and C form a complete graph G of order 4 and therefore are Cross Triangle nodes. Similarly, nodes I, J, K, and L form a complete graph G of order 4, where I, K, and L are collinear. Hence, I, J, K, and L are Hidden Cross Triangle nodes. It is to be noted that the K_h-value of each *CT* or *HCT* node must be ≥ 4.

Non-cross triangle (NCT) nodes. The nodes who form a complete graph G of order $k, \forall\ 0 < k < 4$ are called Non-Cross Triangle nodes. It is clear that nodes those are neither *CT* nor *HCT* are Non-Cross Triangle nodes. As shown in Fig. 2, nodes E, F, G, H, N, O etc. are Non-Cross Triangle nodes.

Common overlapping region (COR). The common overlapping region is defined as the common area of intersection among the coverage area of *CT* or *HCT* or *NCT* nodes. i.e. COR $= \{x \,|\, x \in A \bigcap B$, where A and B are coverage areas of either *CT* or *HCT* or *NCT* nodes$\}$. As shown in Fig. 2, *S* is the common overlapping region formed by coverage areas of nodes *M, A, B,* and *C*.

Candidate node. Any node that wants to move from the redundant region (K_h-value $\geq$ 4) to repair the hole is termed as a candidate node. A candidate node reduces its K_h-value by moving toward the coverage hole. As shown in Fig. 2, common overlapping region *S* formed by nodes *M, A, B,* and *C* is supposed to be minimized. Hence, nodes *M, A, B,* and *C* are candidate nodes. From definition, it is obvious that candidate nodes may be *CT*, *HCT* or *NCT* nodes.

Our main objective is to reduce the K_h-value of the nodes by moving them from the redundant region (K_h-value ≥ 4) to repair the coverage holes. Hence, we would like to derive a relationship between K_h value of a node and *CT* or *HCT* nodes as given in Corollary 1. By using this analysis, we can select the nodes with K_h value of at least 4 as mobile nodes to repair the holes and to reduce their K_h value.

Corollary 1. *K_h-value of a cross triangle or hidden cross triangle node must be at least 4.*

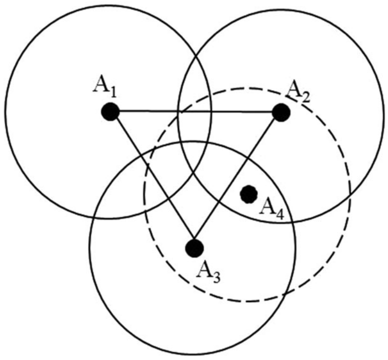

Fig. 3. The ideal case of minimum overlapping area.

Proof. As shown in Fig. 3, let S_{A_1} and S_{A_2} be the sensing disk (coverage area) of node A_1 and A_2, respectively. d_{12} is the distance between locations of node A_1 and A_2 such that $d_{12} < 2R_s$.

$\Rightarrow S_{A_1} \bigcap S_{A_2} \neq \phi$.

Using method of induction, let another node A_3 (S_{A_3} denotes its sensing disk) is deployed such that d_{12}, d_{23}, and $d_{13} < 2R_s$.

$\Rightarrow S_{A_1} \bigcap S_{A_2} \bigcap S_{A_3} \neq \phi$.

$\Rightarrow K_h$-value of these nodes A_1, A_2 and A_3 must be 3.

However, according to definition of *CT* and *HCT* nodes, there must be at least four nodes, which are connected with each other. Hence, deploy another node A_4 such that A_1, A_2, A_3, and A_4 are *CT* or *HCT* nodes.

$\Rightarrow d_{ij} < 2R_s$, where i and $j = 1$ through 4, and $i \neq j$.

$\Rightarrow S_{A_1} \bigcap S_{A_2} \bigcap S_{A_3} \bigcap S_{A_4} \neq \phi$

$\Rightarrow K_h$-value of these nodes A_1, A_2, A_3, and A_4 must be 4.

$\Rightarrow K_h$-value of *CT* nodes is 4, which is also true for *HCT* nodes. Using method of induction for m number of *CT* or *HCT* nodes, it can be deduced that $S = \bigcap_{k=1}^{m} S_{A_k}$, where $k = 1, 2, 3, \ldots, m$ and $m \geq 4$, and S is the COR of those m nodes.

$\Rightarrow K_h$-value of *CT* or *HCT* nodes must be ≥ 4, i.e. must be at least 4. □

3 HORA: The Hole Repair Algorithms

In this section, the coverage HOle Repair Algorithms are developed taking node density of the network. Based on our assumptions, the nodes are deployed randomly and the network is fully connected. Due to random deployment, it could be possible that more number of nodes may overlap with each other in some parts of the network, whereas few number of nodes may overlap in other parts of the network. In such a deployment scenario, the node density of the network can be non-uniform as density of the nodes in the large overlapping area must be higher than the density of the nodes in the sparse region. Besides, it could be possible that coverage hole is generate due to predictable or unpredictable death of the nodes. Hence, our goal is to repair the coverage holes by moving few sensors from the large overlapping area to the hole region so that uniform density of the nodes can be maintained in the whole network. In our algorithms, a mobile node is selected based on its highest coverage degree (K_h) value and the new location of the mobile node is calculated without compromising the coverage and connectivity of the network. In order to maintain an average uniform coverage degree of the network and to repair the coverage holes at the same time, following points are strictly considered.

- Existing connectivity of a mobile node with its one-hop neighbors is not disturbed.
- Existing coverage of a mobile node is not lost.
- K_h value of a node in the region to which another node from the large overlapping region moves, does not change due to such mobility.

The detail procedure of the proposed HOle Repair Algorithm is described as follows.

3.1 Selection of a Mobile Node

After deployment of the nodes, each node checks its status as a *CT*, *HCT* or *NCT* node. Let coverage holes H_1 and H_2 be generated in the network due to death of the nodes and as per our assumption, location of the hole is known. Hence, any node can be a candidate node, which may be a *CT*, *HCT* or *NCT* based on its K_h value. It is to be noted here that K_h value of a *CT* or *HCT* node must be ≥ 4 and that of an *NCT* must be < 4. Then the question arise, which node among those candidate nodes should be selected as a mobile node? Before deciding a candidate node as a mobile one, each candidate node has to collect following four variables from its one-hop neighbors and makes its decision of mobility.

α. Cardinality of set of one-hop neighbors of a candidate node who (1) does not enclose the common overlapping region S and (2) is a *CT* or *HCT* node is denoted by α. For example, as shown in Fig. 2, node A is a candidate node and M, C, B, Q and P are its' one-hop neighbors. Though, nodes M, C, and B are *CT* nodes, they enclose the COR and therefore they do not satisfy the first condition. Similarly, though nodes P and Q do not enclose the COR, they are not *CT* or *HCT* nodes and therefore they do not satisfy the second condition. Under these two conditions, set of one-hop neighbors of candidate node A is NULL and therefore α of A is 0.

β. Cardinality of set of one-hop neighbors of a candidate node, which are *NCT* nodes is denoted by β and is defined as follows.

$$\beta = \begin{cases} x, & \text{if the candidate node is not a boundary node} \\ \infty, & \text{if the candidate node is a boundary node.} \end{cases}$$

For example, as shown in Fig. 2, let A be a candidate node. Since, P and Q are two one-hop neighbors of A, which are *NCT* nodes and A is not a boundary node, β of A is 2. However, for the candidate node M, though it has three one-hop neighbors G, F and P, and are *NCT* nodes, β of M is ∞ as it is a boundary node.

γ. Number of one-hop neighbors of a candidate node as defined below is denoted by γ.

$$\gamma = \begin{cases} 1, & \text{if (have only one } NCT \text{ node;)} \\ & \parallel \text{(have more than one } NCT \text{ nodes,} \\ & \text{which are disconnected with each other;)} \\ 0, & \text{else.} \end{cases}$$

For example, as shown in Fig. 2, let node M be a candidate node. Though G, F, C, A and P are its one-hop neighbors,

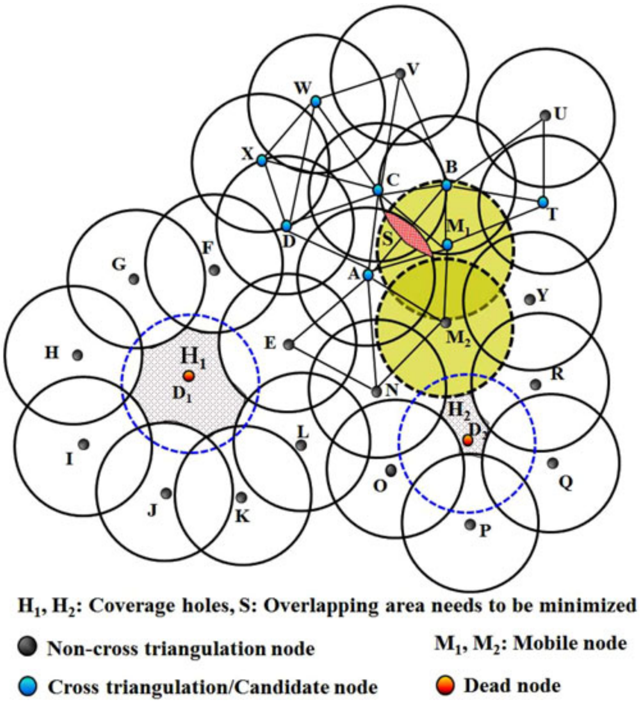

Fig. 4. Selection of mobile node for $K_h < 4$.

only G, F, and P are *NCT* out of which G and F are connected with each other. Hence, γ of M is 0. The same rule is applied to the candidate node A as shown in Fig. 4 and therefore γ of A is 0. In Fig. 4, γ of candidate node B is 1, as two of its one-hop neighbors are *NCT* nodes, which are not connected with each other. Similarly in Fig. 4, γ of candidate node C is 1, as V is only one *NCT* node among its one-hop neighbors.

ρ. Number of intersection points (P_j) between a candidate node and its one-hop neighbors, such that

1) P_j is a covered point and is covered either by two or three sensors.
2) $\overline{C_iP_j} = R_s$, where C_i is the location of one-hop neighbors of a candidate node and R_s is its sensing range.
3) $\overline{C_jP_j} \leq R_s$, where C_j is location of the candidate node and R_s is its sensing range.

The set of intersection points (P_j) which matches the above definition is called V_p.

For α and β or γ value, that information provides the neighbor distribution of a node and we prove that those features can be used to decide the mobile node exactly.

Lemma 1. *The common overlapping region of the cross triangle or hidden cross triangle nodes must be more dense ($K_h \geq 4$).*

Proof. Let us assume that COR S of the *CT* or *HCT* nodes is less dense ($0 < K_h < 4$). According to Corollary 1, the K_h-value of a *CT* or *HCT* node is at least 4. Hence, COR S must be covered by at least four nodes. Let us deploy more nodes to cover the area S such that the area S is enclosed by more *CT* or *HCT* nodes. In other words, the area S will be covered by more than four nodes and becomes more dense ($K_h \geq 4$), contradicting our assumption. Therefore, the area enclosed by more *CT* or *HCT* nodes must be more dense ($K_h \geq 4$) and the K_h value must be higher. □

Lemma 2. *If a node has high value of β or γ, all of its neighbors must not be connected and therefore the deployment of nodes must be sparse.*

Proof. Using method of contradiction, let us assume that all neighbors a node having high value of β or γ are connected and therefore the nodes are densely deployed. As shown in Fig. 2, let us assume that node D_1 is alive and its β values are 2 (H and G) and 3 (N, O, and P). To increase the β value of D_1, let I, J, and L become *NCT* nodes due to failure of K. Hence, β value of D_1 becomes 7 (G, H, J, L, N, O, and P). We can see the area, originally covered by node J, I, K, and L, is covered by less number of nodes, contradicting our assumption. Besides, nodes G, H, J, L, N, O, and P cannot form a complete graph such that their K_h values are 3, which again contradicts our assumption. Therefore, if a node has high value of β or γ, all of its neighbors must not be connected, which implies that the region is covered by more number of *NCT* nodes. Hence, there must be sparse deployment of nodes over that region. □

Lemma 3. *The Covered Point enclosed by the coverage hole must be covered by only two sensors and enclosed by the one-covered area without coverage hole must be covered by only three sensors.*

Proof. It is to be noted that no coverage hole is found if the boundary of sensing disk of a sensor is fully covered by other sensors. Otherwise, there must be a coverage hole. Besides, any point of intersection can be generated by at least two sensors and it must be on the boundary of the sensing disk. As shown in Fig. 1, $\overline{N_7P_4}$ and $\overline{N_7P_6}$ are less than R_s. $\overline{N_2P_4}$ and $\overline{N_4P_6}$ is equal to R_s. P_4 is covered by N_2, N_3, and N_7 and P_6 is covered by N_3, N_4, and N_7.

Using method of contradiction, let us assume that the Covered Point enclosed by the coverage hole is not covered by only two sensors. If N_1 through N_6 become boundary nodes due to failure of N_7, then P_4 and P_6 are covered by only two sensors. Let, there exists a set of nodes I, where $\overline{I_iP_4}$ or $\overline{I_iP_6}$ is less than R_s and $I_i \in I$, for $i > 1$, such that N_2, N_3, or N_4 is not a boundary node anymore. Although P_4 or P_6 is covered by more than two nodes, they are not Covered Points enclosed by the coverage hole, which contradicts our assumption. Hence, the points of intersection enclosed by the coverage hole are covered by only two sensors.

Now, we have to prove that the Covered Point enclosed by the one-covered area without coverage hole must be covered by only three sensors. Considering the method of contradiction, let us assume that Covered Point enclosed by the one-covered area without coverage hole is not covered by only three sensors. As shown in Fig. 1, we still assume that N_1 through N_6 are boundary nodes due to failure of N_7. If there exists a set of nodes called J, where $\overline{J_jP_4}$ and $\overline{J_jP_6}$ are less than R_s and $J_j \in J$, for $j > 1$, then N_2, N_3, or N_4 is not a boundary node anymore. Although, P_4 and P_6 will be covered by more than three nodes, it contradicts our assumption. Hence, the Covered Points enclosed by one-covered area are covered by only three sensors. □

TABLE 1
Neighborhood Information of Candidate Nodes

Node	α (Fig. 2)	β (Fig. 2)	γ	ρ	V_{fn}
M	0	∞	0 (Fig. 2)	6	∞
A	0	2 (P, Q)	0 (Fig. 4)	4	-2
B	4 (D, T, U, V)	∞	1 (Fig. 4)	7	∞
C	1	2 (E, F)	1 (Fig. 4)	6	-5

Corollary 2. *Area bounded by V_p must be 1-covered.*

Proof. Let N_7 be a candidate node and V_p of N_7 be P_4, P_6, P_9, P_{10}, P_{11}, and P_{12}, as shown in Fig. 1. Based on the definition of V_p, these points must be covered either by two or three sensors. Besides, in lemma 3, it is proved that the Covered Points enclosed by the one-covered area without coverage hole must be covered by only three sensors. Therefore, an area enclosed by these points must be one-covered and hence the area enclosed by V_p must be one-covered. □

It is to be noted that either a *CT*, *HCT* or *NCT* node can be a candidate node. If K_h value of a candidate node is ≥ 4, it must be a *CT* or *HCT* node, else it must be an *NCT* node. Hence, in our protocol a cross triangle node gets higher priority to be a mobile node as its K_h value is higher than the non-cross triangle one. Accordingly, we have two possible cases to decide a candidate node as a mobile node as described below.

Case 1: If K_h-value of a candidate node is ≥ 4

As shown in Fig. 2, suppose holes H_1 and H_2 are created due to death of multiple sensors. Here, K_h-value of the boundary nodes (M is a boundary node with respect to hole H_1 and B is a boundary node with respect to hole H_2) is $\geq$ 4. Hence, the one-hop neighbors of the dead node must be either a *CT* or *HCT* nodes and one of those nodes should be selected as a mobile node. Let C be the set of candidate nodes, which are either *CT* or *HCT* nodes and enclose a common overlapping region. Then, each candidate node executes the following steps to decide its role as a mobile node or not.

Step 1. A candidate node collects its own values of β or γ, α and ρ from its one-hop neighbors.

Step 2. It checks if it can be a mobile node or not. A candidate node cannot be a mobile node, if its value of β and γ is zero or has been selected as a mobile node earlier.

Step 3. A candidate node calculates its V_{fn} value as (β - α - ρ), if its $\beta > \gamma$ or $\gamma = 0$, else its V_{fn} value is calculated as (γ - $\alpha - \rho$). For example, as given in Table 1, since γ value of node A is zero, its V_{fn} value is equal to $\beta - \alpha - \rho = -2$.

Step 4. It compares its V_{fn} value with all members of the candidate nodes set C. A candidate node is selected as a mobile node, if it has highest V_{fn} value in set C. For example, as given in Table 1, V_{fn} value of node M is ∞, which is greatest among V_{fn} value of other candidate nodes and therefore is selected as the mobile node.

Step 5. If a candidate node is selected as a mobile one, it moves to a new location. After moving to the new location, it sends its one-hop neighbor's list with a time stamp and loses the qualification to be a mobile node again. The purpose of sending its one-hop neighbor's list is to claim its new location and to initiate the next round.

It is to be noted that the values of β or γ, α, and ρ are gathered first, and then value of V_{fn} for each cross triangle nodes M, A, B, and C is calculated as given in Table 1. The coverage hole H_1 and H_2 are generated due to failure of node D_1 and D_2, respectively. In this case, we mainly consider to repair the coverage hole H_1. As shown in Fig. 2, node B and M are boundary nodes. From Table 1, though V_{fn} value of both nodes B and M is highest and is same, M is selected as the mobile node as it is closer to the coverage hole H_1. If any *NCT* node whose K_h value is < 4 is a boundary one, i.e. if it encloses a coverage hole, a mobile node is selected as given below in Case 2.

Case 2: If K_h-value of a candidate node is < 4

As shown in Fig. 4, the one-hop neighbors of a dead node who enclose either hole H_1 or H_2 are neither *CT* nor *HCT* nodes. Hence, K_h-value of those *NCT* nodes must be < 4 according to definition. In this case, when boundary nodes detect a coverage hole and find the highest coverage degree (K_h-value) of each boundary node that encloses the same hole is less than 4, initially they assume not to move. However, some serious coverage overlapping ($K_h \geq 4$) may be there at some part of the network. Let us assume that the nodes having $K_h \geq 4$ are k-hops away from the location of the coverage hole. Then, we can achieve our goal by moving a node having $K_h \geq 4$ up to one hop and then continue the process until the boundary nodes can be moved to repair the hole. In other words, we minimize the overlapping area of the nodes, which have K_h-value ≥ 4 and are k-hops away from the coverage holes, so that they can repair the hole through cascading mobility. An example of such scenario is shown in Fig. 4 and detail procedure of such method is described as follows.

Step 1. If K_h-value of the boundary node is less than 4, one of them broadcasts a *Mobility Invitation* message to its one-hop neighbors.

Step 2. If K_h-value of any of its neighbors is ≥ 4 (it must be a *CT* or *HCT* node), it executes the steps given in Case 1 to minimize its K_h value. Else, it rebroadcasts the same *Mobility Invitation* message to its next one-hop neighbors and the process continues until it arrives to a *CT* or *HCT* node ($K_h \geq 4$).

Step 3. A *CT* or *HCT* node may receive several *Mobility Invitation* messages simultaneously. However, it considers the coverage hole that is nearest to its location. For example, as shown in Fig. 4, there are two coverage holes H_1 and H_2 and the boundary nodes broadcast *Mobility Invitation* message. Upon receiving the message, node M_1, which has K_h ≥ 4, infers that hole H_2 is closest to its location. Hence, it moves toward the hole H_2 instead of H_1.

Step 4. After mobility of a *CT* or *HCT* node, if its one-hop neighbor's K_h value is still ≥ 4, those nodes execute the steps given in Case 1 and the process continues till *CT* or *HCT* nodes cannot be moved anymore. It is to be noted that mobility of *CT* or *HCT* nodes is limited within one hop.

Step 5. The boundary nodes those are *NCT*, such as node M_2, will be a mobile node if it has the smallest mean value of distances among its one-hop neighbors and itself than others. Thus, in Fig. 4, node M_2 will be the next mobile node. This step will be executed until the boundary nodes around the coverage holes cannot be a mobile one.

Taking Fig. 4 as an example; in the beginning, all boundary nodes that are *NCT* and enclose the coverage hole H_2 send the *Mobility Invitation* message to its one-hop neighbors. Then, node M_1 receives two *Mobility Invitation* messages from node M_2 and node E, respectively. After the procedure of Case 1, M_1 is selected as a mobile node and starts to repair the coverage hole (H_2) that is closest to its location. Finally, M_2 is selected as the mobile node based on Step 5 of Case 2 to repair the coverage hole H_2 after M_1 is moved.

Lemma 4. *If a candidate node is cross triangle or hidden cross triangle node with highest value of β or γ, i.e., if a candidate node has highest V_{fn} and it moves, it can reduce the value of K_h, and therefore can reduce the coverage overlapping area.*

Proof. According to lemma 2, the region corresponding to a node that has higher value of β or γ, must be less dense ($0 < K_h < 4$). It implies that the β or γ is inversely proportional to K_h-value. Moreover, the K_h-value is proportional to the degree of coverage overlapping area. If K_h value can be reduced, the overlapping area is reduced as well.

Consider a set of boundary nodes called S ($S = \{N_p \in S|N_1, N_2, \ldots, N_p\}, p = 1 - |S|$), which is composed of *CT* or *HCT* and encloses the same coverage hole. The β or γ for each N_p is ∞ through 1, respectively. It is to be noted that the value of β or γ and the value of V_{fn} is in direct proportion. Hence, node N_1 has highest value of β or γ, that is, its β or γ value is ∞, which implies that a coverage hole must be enclosed by N_1 and therefore is selected as a mobile node. Thus, N_1 can move toward the mobile region such that its K_h-value will be reduced. The coverage overlapping area of S is reduced, too. We assume that a group of nodes called S_1 ($S_1 = \{N_r \in S_1, S_1 \subset S \mid N_1, N_2, \ldots, N_r\}, r = 1 \mid S_1|$), where the β or γ of N_1 through $N_{|S_1|}$ is ∞ through $|S_1|$, is moved to repair the coverage hole, then the overlapping area of S and its K_h value are reduced. Now, one more node called $N_{|S_1|+1}$, where $N_{|S_1|+1} \in S$, is the next mobile node. Since, S_1 has reduced the overlapping area and $N_{|S_1|+1}$ is moved to its mobile region, the K_h value of S and its overlapping area are reduced.

Furthermore, in Condition 3, we justify that the K_h value of one-hop neighbors of a mobile node does not increase after its mobility. Therefore, if a candidate node that has highest value of V_{fn} is selected as a mobile node and it moves, the K_h value will be reduced and therefore the coverage overlapping area is reduced. □

Lemma 5. *If a non-cross triangle node with smallest mean value of distances between all of its one-hop neighbors and itself can move to repair a hole, it can reduce the coverage overlapping.*

Proof. The size of coverage overlapping area between two nodes is directly proportional to the distance from one center of a node to the other. If the mean value of the distances between a node and all of its one-hop neighbors is least, it implies that the overlapping area is much larger. Thereby, it can be used to judge the degree of overlapping area.

Consider a group of boundary nodes called B ($B = \{N_p \in B|N_1, N_2, \ldots, N_p\}, p = 1 - |B|$), which contains *NCT* nodes ($K_h < 4$) and encloses the same coverage hole. The mean values of N_1 through $N_{|B|}$ increase toward the highest, which implies that the size of overlapping area of N_1 is largest. In our algorithm, when N_1 is selected as a mobile node, a mobile region is also determined, which is less dense ($0 < K_h < 4$) for N_1 and is described later. Then, N_1 is moved toward the mobile region to repair the coverage hole. In the view of minimizing overlapping area, N_1 can reduce more overlapping area than the next mobile node such that the overlapping area of B can be reduced. It is assumed that if a group of nodes called B_1 ($B_1 = \{N_r \in B_1, B_1 \subset B \mid N_1, N_2, \ldots, N_r\}, r = 1 - |B_1|$), where the mean values and K_h values of $N_{|B_1|}$ through N_1 become least, is moved to repair the coverage hole first, then the overlapping area of B is reduced. Now, one more node called $N_{|B_1|+1}$, where $N_{|B_1|+1} \in B$, is the next mobile node. Since, B_1 has reduced the overlapping area of B and $N_{|B_1|+1}$ is moved to its mobile region, the overlapping area of B can be decreased. Therefore, if a node with smallest mean value of distances between all of its one-hop neighbors and itself is moved toward the sparse region, it can reduce the overlapping area. □

3.2 Determination of Mobile Region

The region to which a mobile node should be moved so that its existing connectivity and coverage is not disturbed is called the mobile region (R). In order not to disturb the existing coverage and connectivity, each candidate node first determines its mobile region before it moves to repair the hole. Hence, each candidate node that wants to move to repair the hole, selects its nearest one-hop candidate node as an *assistant node*.

Let, U be the communication disk of the assistant node of the mobile node and V be the one-covered region of the mobile node. Let, E be the 0-covered region of the dead node that overlaps with U and is enclosed by the mobile node. Then, the mobile region $R = (V \cap U) \cup E$. For example, as shown in Fig. 5, let M be the mobile node and A be its assistant node. The dotted circle represents the communication range (R_c) of node A, where $R_c = 2R_s$. The region R_1 will be the mobile region for node M. It is to be noted that the new location of mobile node should not be out of the boundary of its mobile region. As shown in Fig. 5, it is obvious that a mobile node does not loss its existing coverage and connectivity as long as its mobility is limited within the mobile region R_1.

Lemma 6. *If a mobile node moves within its mobile region, its connectivity is not lost and it does not create any coverage hole.*

Proof. Since, the boundary of the mobile region must be less than or equal to the communication range of an assistant node, a mobile node must be connected with at least one node even after its mobility to a new position. Hence, the connectivity is not lost. Besides, the mobile region includes the one-covered area of mobile nodes. According to Corollary 2, the area enclosed by V_p is one-covered. If the new position of the mobile node can still cover its one-covered area, then the existing coverage of mobile node will not be disturbed. To assure that the one-covered area will not be disturbed, we set a moving condition as given in Condition 2 such that the one-covered area is not lost. □

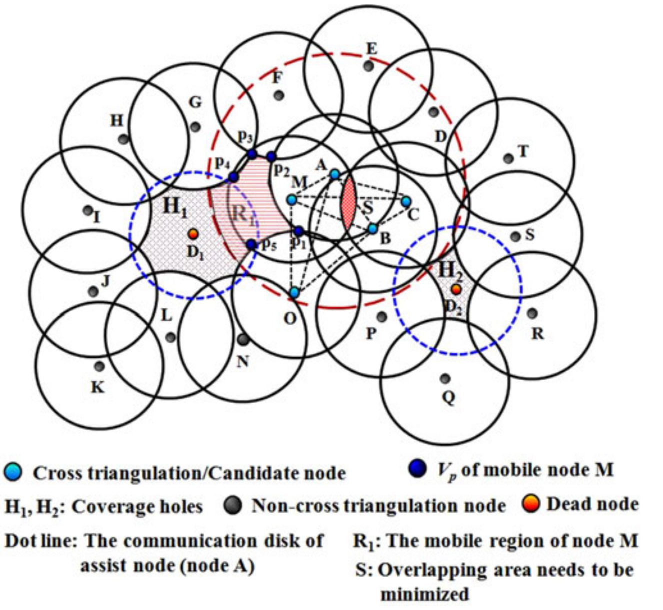

Fig. 5. Example of V_p of mobile node M.

3.3 Calculation of New Location

After selecting the mobile sensor and deciding the mobile region, each mobile node has to find out its new location of mobility. The new location can be calculated by using nonlinear programming, taking minimization of coverage overlapping as the objective function and conditions of mobility as the constraints. Let, (X_n,Y_n) be the new position of the mobile node, which is to be calculated. Then, mobility of the node to that new position must satisfy the following conditions.

Condition 1. *Existing connectivity with at least one of the one-hop neighbors of the mobile node is not lost.*

In order to achieve this condition, find set of neighbors (N_o), which are boundary nodes or one-hop neighbors of the mobile node and whose sensing disks enclose the mobile region of that mobile node. Of course, N_o also includes the assistant node of mobile node. Let, new position of the mobile node be (X_n,Y_n) and coordinate of each member of N_o = (X_j,Y_j). In order to achieve Condition I, following in-equation should be satisfied.

$$(X_n - X_j)^2 + (Y_n - Y_j)^2 \leq R_c^2 \quad (1)$$

For example, as shown in Fig. 5, M is the mobile node and O, A, F, and G are members of N_o. After mobility of node M, nodes O, A, F, and G should be connected with it.

Condition 2. *Existing coverage of the mobile node is not lost.*

In order to satisfy this condition, find set of points of intersections (V_p) , which are covered by the mobile node and exactly by another one or two sensors. Let, (X_n,Y_n) be the new position of the mobile node and coordinate of each point of V_p be (X_p,Y_p). In order to achieve Condition 2, following in-equation should be satisfied.

$$(X_n - X_p)^2 + (Y_n - Y_p)^2 \leq R_s^2 \quad (2)$$

For example, as shown in Fig. 5, M is the mobile node and P_1, P_2, P_3, P_4, and P_5 are the points of intersections and

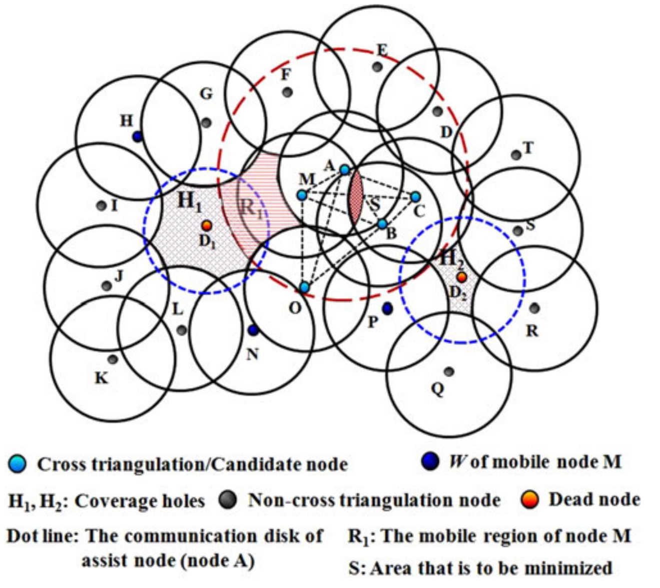

Fig. 6. Example of W of mobile node M.

members of V_p. From the figure, it is obvious that existing coverage of the mobile node M is not lost after its mobility.

Condition 3. *K_h-value of one-hop neighbors of the mobile node is not increased.*

In order to satisfy this condition, find the set of nodes (W), which are one-hop neighbors of boundary nodes and are two-hops away from the mobile node. Let, (X_n,Y_n) be the new position of the mobile node and the coordinate of each member of W be (X_d,Y_d). In order to achieve condition 3, following in-equation should be satisfied.

$$(X_n - X_d)^2 + (Y_n - Y_d)^2 > R_c^2. \quad (3)$$

For example, as shown in Fig. 6, M is the mobile node and nodes H, N, and P are the members of W. From the figure, it is obvious that K_h value of nodes G and O is not increased due to mobility of node M.

Lemma 7. *If a convex region is fully covered and a node of that region moves to a new position such that the distance between its new position and its V_p is less than or equal to R_s, the exiting coverage is not disturbed.*

Proof. We emphasize that if an area within a sensing disk is one-covered, then each point of V_p of that node must be on the boundary of the one-covered area (based on Corollary 2). Moreover, the size of one-covered area must be less than the sensing disk of a node. As shown in Fig. 7, we assume that each point of set V_p of node A_4 is called $P_i(V_p = \{P_i \in V_p \mid P_1, P_2, \ldots, P_i\}, i = 1 - |V_p|)$, and the corresponding distance between A_4 and point P_i is called D_i.

Suppose A_4 is moved to the new position. If D_i is greater than R_s, then the set V_p of A_4 is not fully covered by only three sensors and the coverage hole is generated. Consider the region Q, which is enclosed by $\widehat{P_3P_4}$ and $\overline{P_3P_4}$. Since, $\widehat{P_3P_4}$ is on the boundary of sensing disk of N_4, that region Q will be covered by N_4, if D_3 and D_4 are less than R_s simultaneously. Besides, consider the

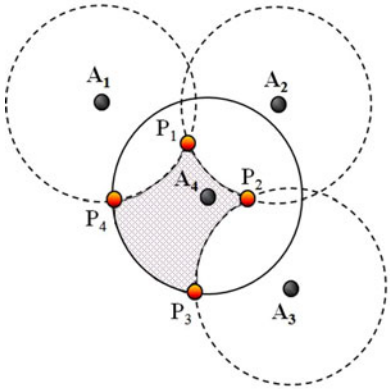

Fig. 7. One-covered area enclosed by V_p.

polygon R, which is enclosed by $\overline{P_1P_2}$, $\overline{P_2P_3}$, $\overline{P_3P_4}$, and $\overline{P_1P_4}$. The set V_p of N_4 is the vertex of polygon R. If D_1 through D_4 is less than or equal to R_s, then R is always within the sensing disk of N_4. In our algorithm, each P_i must be covered by A_4 simultaneously after its mobility such that $D_i \leq R_s$. Hence, the region, which is composed of Q and R, is in the sensing disk of N_4. Obviously, the region that Q pluses R, is larger that the one-covered area of N_4. Therefore, if the distance between the new position of a node and its V_p is less than or equal to R_s, then the existing coverage is not disturbed. □

Lemma 8. *If distance between the new position of a mobile node and position of any element of* W *is greater than* R_c, *the highest coverage degree* (K_h) *of one-hop neighbors of the mobile node before its mobility is not increased.*

Proof. We assume that the distance between the new position of mobile node A and each node of W of A is called M_m, where $m = 1 - |W|$. The new position of A is called A'. Since, A' is located at the sparse region, such as coverage hole or one-covered area of A, we find a set of nodes called S, which are boundary nodes and are one-hop neighbors of A. Taking Fig. 6 as an example; node O and G belong to set S with respect to coverage hole H_1. Furthermore, set S and W overlap with each other before mobility. Hence, the K_h value of S and W must be > 2.

Using method of contradiction, let us assume that the distance between A' and A's W be greater than R_c. Then, the K_h-value of one-hop neighbors of A will be increased. Let, A is moved to A' such that the K_h value of W and S is decreased at least by 1. However, if M_m is greater than R_c, then the K_h value of W and S will not be increased, which contradicts to our assumption. Besides, suppose $M_m > R_c$ and the distance between A' and S is less than or equal to R_c. If A is moved to A' such that A overlaps W, then the K_h value of S and W must be > 3. Therefore, if the distance between the new position of a mobile node and its W is greater than R_c, then the highest coverage degree of one-hop neighbors of the mobile node will not be increased. □

Let B' (X_n,Y_n) be the new position of the mobile node M. $M(X_j,Y_j)$ belongs to N_o. D is the distance between node M and B' such that $D = \sqrt{(X_n - X_j)^2 + (Y_n - Y_j)^2}$.

Let, A_j be the overlapping area between M and B'. To find the overlapping area A_j, we have to simplify the position of node M and B'. Suppose, M is centered at $M(0,0)$ and B' is centered at B' $(D,0)$ along X-axis. For any point (X,Y), which is on the sensing disc of M can be represented as

$$X^2 + Y^2 = R_s^2. \tag{4}$$

Similarly, for any point (X, Y), which is on the sensing disc of B' can be represented as

$$(X - D)^2 + Y^2 = R_s^2. \tag{5}$$

Substituting (5) in (4), value of Y can be derived as follows and then substitute the value of Y in (4) to get the value of X as follows:

$$X = \frac{D}{2}, Y = \pm\left(R_s^2 - \left(\frac{D}{2}\right)^2\right)^{\frac{1}{2}}. \tag{6}$$

Hence, points of intersection between M and B' are $(\frac{D}{2}, \pm(R_s^2 - (\frac{D}{2})^2)^{\frac{1}{2}})$. To find the overlapping area A_j along Y-axis, let $X = f(Y)$. Taking the limits of integration from $+\sqrt{R_s^2 - (\frac{D}{2})^2}$ to $-\sqrt{R_s^2 - (\frac{D}{2})^2}$ and using (4) and (6), overlapping area A_j can be calculated as follows:

$$A_j = 2\int_{-\left(R_s^2-\frac{D^2}{4}\right)^{\frac{1}{2}}}^{\left(R_s^2-\frac{D^2}{4}\right)^{\frac{1}{2}}} \left(R_s^2 - Y^2\right)^{\frac{1}{2}} dY. \tag{7}$$

Let, θ be $\sin^{-1}\frac{Y}{R_s}$. Substituting it in (7) and solving the integration for $\cos^2\theta$, we get

$$A_j = 2R_S^2\left[\frac{1}{2}\theta + \frac{1}{4}\sin 2\,\theta \Big|\begin{smallmatrix} R_s^2\sin\theta \\ -R_s^2\sin\theta\end{smallmatrix}\right]. \tag{8}$$

Substituting $\pm(R_s^2 - \frac{D^2}{4})^{\frac{1}{2}}$ in (8), the result of integration can be obtained as follows:

$$\begin{aligned} A_j = R_S^2 \Bigg[& \sin^{-1}\frac{\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s} - \sin^{-1}\frac{-\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s} \\ & + \frac{\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s}\cos\sin^{-1}\frac{\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s} \\ & + \frac{\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s}\cos\sin^{-1}\frac{-\left(R_s^2 - \frac{D^2}{4}\right)^{\frac{1}{2}}}{R_s}\Bigg]. \end{aligned} \tag{9}$$

Assuming $\sin^{-1}\frac{(R_s^2-\frac{D^2}{4})^{\frac{1}{2}}}{R_s} = \gamma$ and substituting it in (9), it can be derived as

$$A_j = R_s^2[2\gamma + \sin 2\gamma]. \tag{10}$$

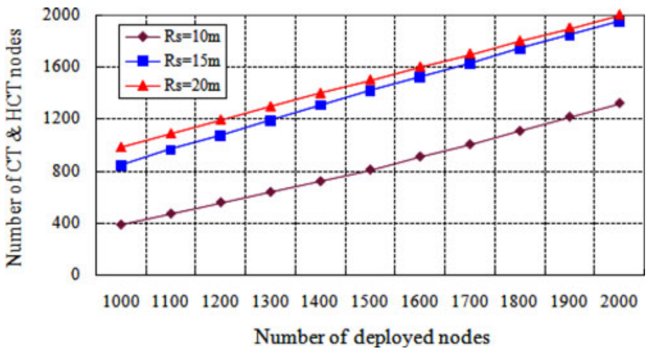

Fig. 8. Number of (hidden) cross triangulation nodes with different sensing range.

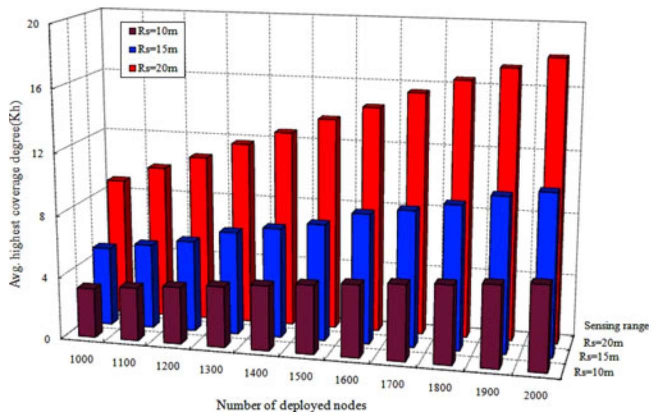

Fig. 9. Average highest coverage degree (k_h) with different sensing range.

Furthermore, equation (10) can be rewritten as

$$A_j = 2R_s^2 \tan^{-1}\frac{(4R_s^2 - D^2)^{\frac{1}{2}}}{D} + \frac{D}{2}(4R_s^2 - D^2)^{\frac{1}{2}}. \tag{11}$$

Substituting D in (11), we get

$$\begin{aligned} A_j = {} & 2R_s^2 \tan^{-1}\left(\frac{(4R_s^2 - ((X_n - X_j)^2 + (Y_n - Y_j)^2))^{\frac{1}{2}}}{((X_n - X_j)^2 + (Y_n - Y_j)^2)^{\frac{1}{2}}}\right) \\ & + \frac{((X_n - X_j)^2 + (Y_n - Y_j)^2)^{\frac{1}{2}}}{2} \\ & (4R_s^2 - ((X_n - X_j)^2 + (Y_n - Y_j)^2))^{\frac{1}{2}}. \end{aligned} \tag{12}$$

It is to be noted that (12) stands for the size of the overlapping area between the new position (B') and any member (M) of N_o. To calculate the total size of the overlapping area, we sum up the overlapping areas between B' and each member of N_o. Minimizing the overlapping area A_j, we can get the new position of the mobile node. Hence, taking the overlapping area A_j as the objective function Z and conditions of the mobility as the constraints as given in (13) through (16), solution of the objective function can give the new position of the mobile node.

$$Minimize\ Z = \sum_{j=1}^{|N_o|} A_j. \tag{13}$$

Subjects to:

$$(X_n - X_j)^2 + (Y_n - Y_j)^2 \leq R_c^2 \tag{14}$$

$$(X_n - X_p)^2 + (Y_n - Y_p)^2 \leq R_s^2 \tag{15}$$

$$(X_n - X_d)^2 + (Y_n - Y_d)^2 > R_c^2. \tag{16}$$

Since, coverage overlapping can occur due to mobility and deployment of new nodes, our protocol can select mobile nodes based on their highest degree of coverage overlapping. Since, mobility raises the issue of connectivity, our protocol selects mobile nodes in such a way that connectivity among the nodes is not disturbed.

Theorem 1. *The solution of minimizing overlapping area for maximizing the coverage area is unique.*

Proof. Let us assume that if the overlapping area is minimized, the coverage area can still be maximized. As shown in Fig. 3, suppose that A_4 is the new position of A_3. Then, the overlapping area is minimized but the coverage area can still be maximized. However, based on our objective function and conditions of mobility, if A_4 cannot cover V_p of A_3, then A_4 does not correspond to (15) as new coverage hole is generated. Besides, suppose that $\overline{A_1A_4}$ and $\overline{A_2A_4}$ are greater than R_c such that the coverage area can be maximized. But, the connectivity is lost as B disobeys (14). Last but not least, if A_4 does not correspond to (16), then the overlapping area is not maximized in that A_4 let the K_h value of W of A_3 be increased. It implies that the overlapping area of A_3 becomes larger after its mobility, which contradicts to our assumption. Therefore, the position of A_4 is same as A_3. That is, based on our algorithm, once the overlapping area is minimized, the coverage area is also maximized. □

4 Performance Evaluation

The proposed protocol is simulated using ns-2.32 in which 1,000 nodes are deployed randomly over an area of size 300×300 m. Based on our assumption, communication range is taken to be twice of the sensing range and IEEE 802.15.4 MAC with TwoRayGround propagation model is considered in our simulation. The initial energy of a node is taken to be 50J and energy consumption due to mobility is taken to be 1 J/m. The simulation is run for 20 different topologies and average value of the all runs is presented in the simulation result. In our algorithm, the number of *CT* and *HCT* nodes play an important role to decide the mobility. Hence, as shown in Fig. 8, possible number of *CT* and *HCT* nodes are simulated by deploying 1,000 to 2,000 nodes randomly with different sensing ranges of 10, 15, and 20 m. Apparently, the number of *CT* and *HCT* nodes is increased linearly with the number of deployed nodes.

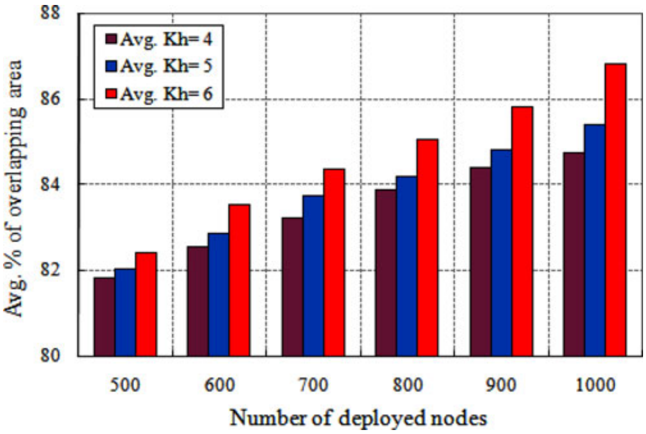

Fig. 10. Average percentage of overlapping area with different K_h value (500-1000 nodes).

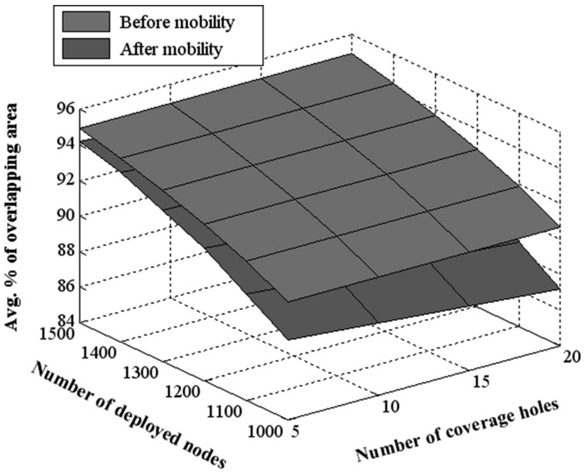

Fig. 12. Variation of average percentage of overlapping area between before mobility and after mobility.

As shown in Fig. 9, the average highest coverage degree (k_h value) escalates when more nodes are deployed. It implies that the density of nodes (K_h value) is directly proportional to the number of *CT* and *HCT* nodes. It is noticed that the higher the density of deployment and longer the sensing range for each node we deploy in a monitoring area, the more *CT* and *HCT* nodes can be used to minimize the overlapping and maximize the coverage area. Furthermore, we simulate the effect of average K_h value over the average percentage of overlapping area for different number of deployed nodes in Fig. 10. The average percentage of overlapping area is increased if the number of deployed nodes is increased for the same average K_h value. The average percentage of overlapping area is increased linearly with K_h value for the same number of deployed nodes. Hence, our algorithm is suitable for highly dense deployment scenario. In order to justify our algorithm for moving the *NCT*, *CT*, or *HCT* nodes, we simulated the variation of average K_h value and average percentage of coverage overlapping before and after the mobility of nodes. The simulation results are given as follows.

4.1 Simulation Results

As shown in Figs. 11 and 12, we simulated the variation of K_h value and average percentage of overlapping area, respectively. Both works are simulated before and after the mobility of nodes. As shown in Fig. 11, more average value of K_h can be reduced after mobility, if there are more coverage holes. It is found that performance in terms of average K_h value is better for less number of deployed nodes. It is very interesting to see that average K_h value is reduced after mobility and this result complies with our protocol. Similarly, as shown in Fig. 12, the average percentage of overlapping area is decreased more if there are more coverage holes. Besides, the average percentage of overlapping area is decreased more if less number of nodes are deployed. Based on our simulation results, the average overlapping area is minimized after mobility without increasing the average K_h value in monitoring area. That is, the result matches the third conditions of mobility with respect to the objective function.

In our algorithm, different degrees of overlapping area affects the mobility distance and percentage of the hole recovery area. As shown in Fig. 13, we observe that the average mobility distance of the nodes decreases when the average percentage of the overlapping area increases. The average mobility distance is less if more number of nodes are deployed. When 500 nodes are deployed, a longer mobility distance is required to repair the coverage holes as multiple larger coverage holes are formed due to sparse

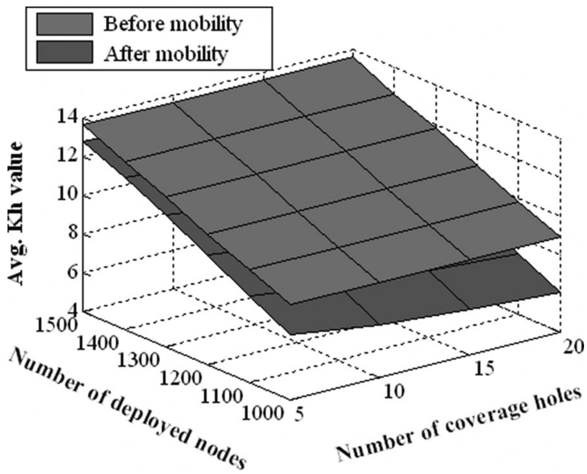

Fig. 11. Variation of K_h value between before mobility and after mobility.

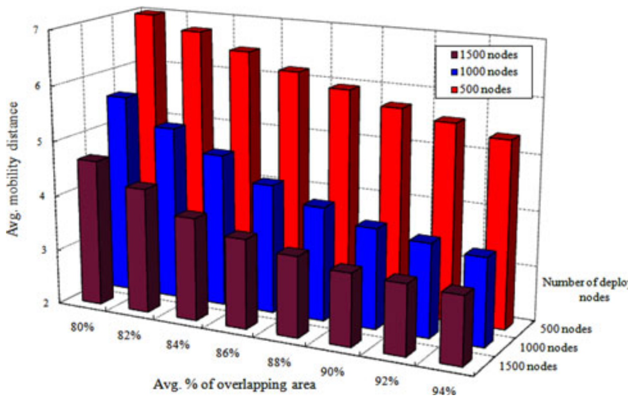

Fig. 13. Average mobility distance (m) with different degrees of overlapping area.

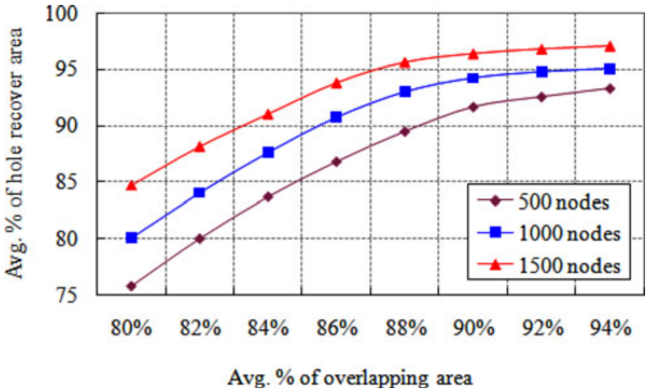

Fig. 14. The percentage of hole recover area with different degrees of overlapping area.

deployment. As shown in Fig. 14, the average percentage of hole recovery increases if more nodes overlap with each other. If more number of nodes are deployed, better percentage of coverage holes can be repaired as more nodes generate higher coverage overlapping. Therefore, it shows that our algorithm is quite suitable for the wireless sensor networks as nodes are deployed densely.

In Figs. 15 and 16, we limit the number of mobile nodes with different mobility distance and different K_h values, respectively to observe the variations of the percentage of hole recovery area. Fig. 15 shows that, for the limited number of mobile nodes, the percentage of hole recovery is increased linearly with the average mobility distance. Fig. 16 presents the percentage of hole recovery area for different K_h values. We can find that the performance of average $K_h = 8$ is worse than $K_h = 9$ or 10. Undoubtedly, the higher K_h value increases the degree of percentage of overlapping area, which totally matches the result in Fig. 14. With high density deployment of sensors, our work is indeed able to improve the percentage of coverage when coverage holes are generated.

Performance analysis of mobility distance is a very important issue in mobile sensor networks, as it affects the power consumption of nodes. To analyze the mobility distance of the nodes, we have simulated our distributed Hole Repair Algorithm and have compared it with similar mobility protocols, such as *Minimax* [24] and *DCM* [29]. In order to compare the performance of our protocol

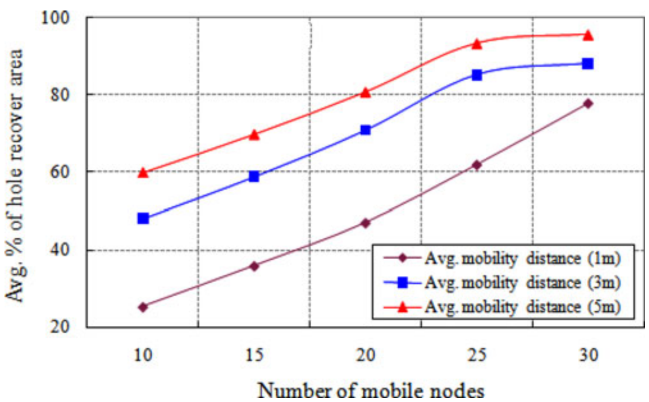

Fig. 15. Average percentage of hole recovery area with different mobility distances.

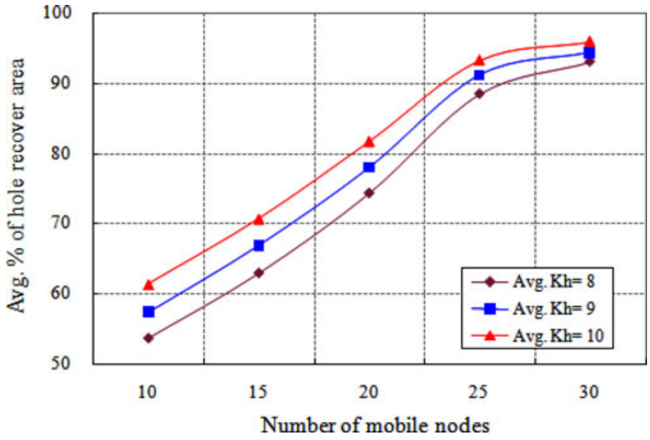

Fig. 16. Average percentage of hole recovery area with different highest coverage degree (K_h).

(*HORA*) with others, we simulated it for single and two-hops scenario. The summary of our evaluation with other protocols is given in Table 2. As shown in Fig. 17, *HORA* outperforms *DCM* in terms of average mobility distance. Although average mobility distance of a node in *Minimax* is less than our work, nodes which enclose the coverage hole have to involve in the process of repairing coverage holes and the increment of mobile nodes is in proportion to the number of deployed nodes, as shown in Fig. 18.

As shown in Fig. 18, the average number of mobile nodes in *DCM* is similar to our protocol for one-hop mobility, but average mobility distance is much longer than *HORA* and *Minimax* as shown in Fig. 17. Since *DCM* decides the maximum mobility distance for each mobile node, the average mobility distance increases in line with size of the coverage hole. As shown in Fig. 17, we also observe that for high density deployment of nodes, such as the case from 1,100 to 2,000 nodes, the average mobility distance in *HORA* and *Minimax* will not change so fast. This situation arises as the most coverage holes are smaller in size and is repaired by less number of mobile nodes with shortest mobility distance. As shown in Fig. 18, the number of mobile nodes with two-hop mobility is more than one-hop mobility, although it is not same as in *Minimax*. The average mobility distance decreases gradually, as shown in Fig. 17, in case of *HORA* (one-hop mobility) and two-hop *HORA*, which implies that energy consumption due to mobility is less.

As shown in Fig. 19, we simulated the average energy consumption of a mobile node with mobility distance of just 1 meter for different numbers of deployed nodes. It is found that the energy consumption in *DCM* is increased linearly

TABLE 2
Summary of the Evaluation

Protocol	Avg. mobility distance	Avg. ♯ of mobile nodes	Avg. energy consumption	Avg. % of alive nodes
DCM	longest	less	much more	worst
Minimax	shorter	much more	a little more	good
HORA	short	less	less	better
2-hop HORA	shortest	more	less	best

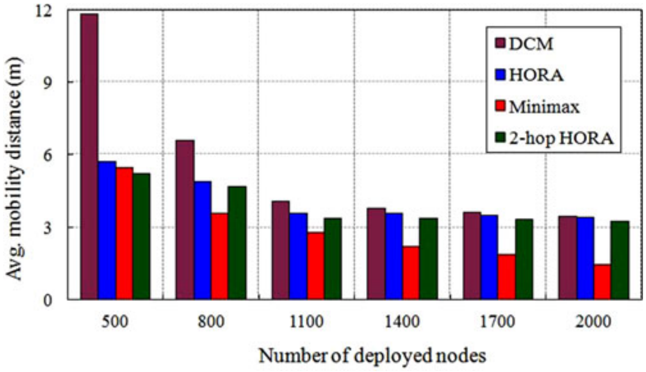

Fig. 17. Average mobility distance for different number of deployed nodes.

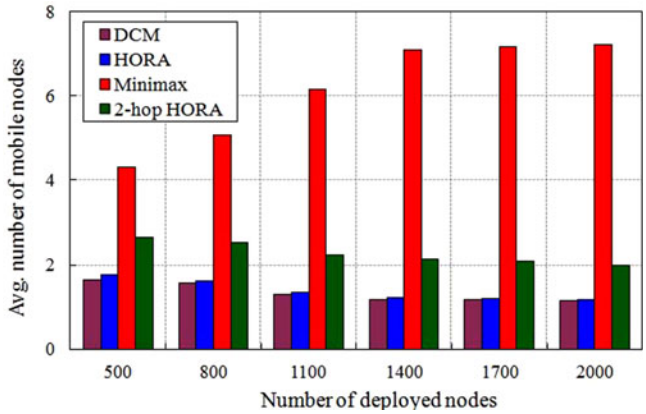

Fig. 18. Average number of mobile nodes for different number of deployed nodes.

with the number of deployed nodes. Higher number of beacon messages consume a great amount of energy and those messages are increased linearly with number of deployed nodes. Besides, the mobility distance and the number of mobile nodes greatly affect the lifetime of the nodes as well. The energy consumption in *DCM* due to mobility and beacon message is higher than *HORA*, *two-hop HORA* and *Minimax*. Therefore, the energy consumption in *DCM* is far larger than our protocol and *Minimax*. However, the energy consumption in *HORA* and *Minimax* is not so much.

As shown in Fig. 20, we analyzed the variation of number of alive nodes versus time. It is observed that in terms of average percentage of alive nodes, *HORA* and 2-hop *HORA* protocol outperforms over *Minimax* as well as *DCM*. The performance of *DCM* is worse than *HORA* and *Minimax*, as average mobility distance and beacon message overhead in *DCM* is much higher than *HORA* and *Minimax*. The beacon message overhead is similar to other cases (*Mininmax*, *HORA*, and two-hop *HORA*). In addition, although the mobility distance of *Minimax* in Fig. 17 is less than our method, whereas the number of mobile nodes is far more than *HORA*, our method outperforms *Minimax* in terms of the percentage of alive nodes. We deploy more nodes (1,000 deployed nodes in this case) such that the density gets higher, and we can predict the number of alive nodes of *Minimax* will decrease gradually. Besides, in two-hop *HORA*, the number of mobile nodes to repair the coverage holes is slightly more than

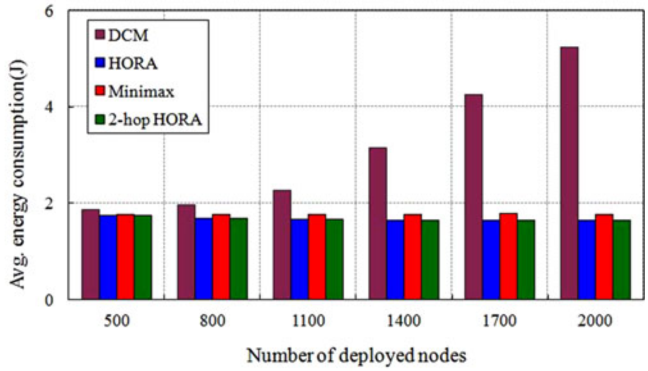

Fig. 19. Average energy consumption for each mobile node with limited mobility distance (1 m).

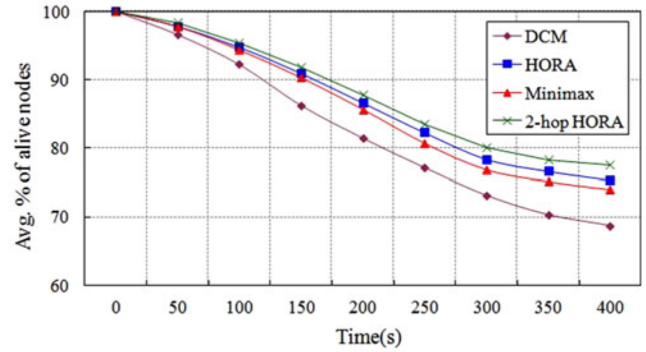

Fig. 20. The percentage of alive nodes during 400 seconds.

HORA. However, the energy cost is shared among more mobile nodes than *HORA* with shorter mobility distance; thereby, the number of alive nodes in case of two-hop *HORA* is slightly higher than *HORA*.

5 CONCLUSIONS

Based on the concept of minimizing the coverage overlapping area to maximize the coverage area, an efficient hole repairing algorithm is proposed by maintaining the connectivity and coverage of the nodes. The coverage hole repair algorithms are designed to maintain the coverage and connectivity of the networks with help of limited mobility of the nodes. Distributed algorithms are designed to select the mobile nodes based on their degree of coverage overlapping (K_h-value) and the calculation of the new positions is made by using nonlinear programming method. Moreover, uniform density of the network is maintained by not increasing the highest coverage degree of the neighbors of any mobile node due to its mobility. Throughout our paper, mobility of a node is limited within one hop, and therefore power consumption due to mobility is least. From the performance evaluation, it is observed that our algorithm outperforms in terms of energy consumption and percentage of coverage hole repair as compared to similar mobility protocols.

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Prasan Kumar Sahoo received the master of science degree in mathematics from Utkal University, India, in 1994, and master of technology degree in computer science from the Indian Institute of Technology (IIT), Kharagpur, India, in 2000. He received the first PhD degree in mathematics from Utkal University, India, and the second PhD degree in computer engineering from National Central University, Taiwan, in 2002 and 2009, respectively. He is currently an associate professor in the Computer Science and Information Engineering Department and director of International Cooperation Center of Chang Gung University, Taiwan. He has been an associate professor in the Department of Information Management, Vanung University, Taiwan and was in the Software Research Center of National Central University, Taiwan. His current research interests include coverage connectivity issues and performance analysis of Wireless Sensor Networks, scheduling problems in Cloud Computing and Big Data analytic. He has served as the Program Committee Member of several IEEE, ACM and international conferences and Program Chair of ICCT 2010. He is a member of the IEEE and ACM.

Wei-Cheng Liao received the BS degree from Ming Chuan University, Taiwan, and the MS degree in Yuan-Ze University, Taiwan. He is currently an engineer in the Institute for Information Industry (III), Taiwan. His research interest includes wired/wireless networks, network security, and secure cloud computing. In terms of wired/wireless networks, he particularly focuses on Diffserv and wireless mobile networks, such as mobile IPv6, Mobile Ad-hoc Networks, Wireless Sensor Networks, and Vehicular Ad-hoc Networks. Besides, he has concentrated on secure routing, key management, intrusion detection system, and cryptography since 2004. When he was a research assistant at Ming Chuan University in 2010, he mainly dealt with the black hole attacks through intrusion detection system in Mobile Ad-hoc Networks. He is focusing on Smart Grid when working for III. He is a member of the IEEE.