Ad Hoc Networks 46 (2016) 12–22

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Dynamic deployment of randomly deployed mobile sensor nodes in the presence of obstacles

Mrutyunjay Rout*, Rajarshi Roy

Department of Electronics and Electrical Communication Engineering, Indian Institute of Technology, Kharagpur, India

ARTICLE INFO

Article history:
Received 3 November 2015
Revised 20 February 2016
Accepted 7 March 2016
Available online 31 March 2016

Keywords:
Coverage
Connectivity
Mobile sensor network
Node deployment
Virtual force

ABSTRACT

For random deployment of wireless sensor networks in a specified geographical location and in the presence of obstacles, optimal network coverage is highly desirable while maintaining network connectivity. In this piece of work, we propose an efficient autonomous deployment scheme, named as Obstacle Avoidance Virtual Force Algorithm (OAVFA), for self-deployment of randomly scattered homogeneous as wells as heterogeneous mobile sensor nodes over a squared sensing field to enhance the network coverage and ensure the network connectivity in the presence of obstacles. Our proposed approach is localized in the sense that each decision taken by the sensor node is strictly based on information acquired from its neighbors. The simulation results show that OAVFA provides an efficient self-deployment of mobile sensor nodes in the presence of obstacles.

1. Introduction

Nowadays, Wireless Sensor Networks (WSNs) have attracted tremendous research interest due to its various applications from environment monitoring, battlefield surveillance, target tracking, wildfire detection, precision agriculture, smart homes and offices, industrial process monitoring and asset management [1]. A mobile sensor network is a collection of inexpensive, low-powered, small size, and multifunctional mobile sensor nodes. The effectiveness of WSNs mainly depends on the network coverage, lifetime and connectivity provided by the sensor deployment strategies such as deterministic and random deployment. Placing sensor nodes manually in predetermined positions on the basis of simple geometric structure (e.g., Hexagon, Square, Rhombus, and Triangular Lattice) is simple and optimal, but this deployment strategy is not suitable in many applications where the application environment is unknown, hostile or inhospitable. For these applications, sensor nodes are required to be deployed randomly by means of dispersing sensors from aircraft or artillery ordinance.

An efficient self-deployment algorithm is highly required to ensure optimal network coverage while maintaining connectivity for such randomly deployed sensors. Presently, virtual force-based self-deployment strategies are adopted to overcome the limitations exhibited by random deployment [2–10]. In this work, an efficient distributed self-deployment algorithm has been proposed for randomly deployed homogeneous as well as heterogeneous mobile sensor nodes. This algorithm is named as Obstacle Avoidance Virtual Force Algorithm (OAVFA). Experimental results carried out with our proposed algorithm not only maximizes coverage area but also ensures the connectivity between all sensor nodes in the presence of obstacles. A set of sensor nodes with identical speeds, communication ranges, and sensing ranges has been identified as homogeneous sensor nodes while heterogeneous sensor nodes differs only in the sensing ranges which are strictly different for various sensors. It has been assumed that the speeds and the communication ranges for heterogeneous sensor remain constant during the process.

The proposed algorithm is localized and executed at each sensor node. In this algorithm, each sensor node considers all attractive and repulsive virtual forces due to its neighboring sensor nodes, obstacles, and the sensing field boundary to determine its movements to enhance the network coverage while maintaining connectivity, prevent the sensor nodes from moving out of sensing field boundary, and avoid the obstacles. Here neighbor sensor nodes of ith sensor s_i means the sensor nodes that are within the communication range of s_i.

In the next section, a brief but latest literature surveys on sensor node deployment has been outlined. Section 3 provides a basic discussion about the network coverage and sensing model. Our proposed deployment algorithm, Obstacle Avoidance Virtual Force Algorithm (OAVFA) has been de-

* Corresponding author. Tel.: +91 947 5411539.
E-mail addresses: mrutyunjay.rout@gmail.com (M. Rout), royr@ece.iitkgp.ernet.in (R. Roy).

http://dx.doi.org/10.1016/j.adhoc.2016.03.004

scribed in Section 4. In Section 5, simulation results are presented followed by conclusions in Section 6.

2. Related work

Sensor arrangement is an imperative issue for some essential objectives in WSNs like coverage, lifetime, and connectivity. For randomly deployed sensor networks, an efficient deployment algorithm is required to self-deploy the mobile sensor nodes to maximize coverage area, ensure the network connectivity and prolong the network lifetime. In [2,3], an incremental and greedy algorithm is presented in which nodes are deployed one at a time. The objective is to maximize the coverage under the constraint that nodes maintain line of sight with each other. Howard et al. [4] have presented a centralized deployment approach based on potential field theory to deploy the mobile sensor nodes (mobile robots) in an unknown environment to enhance the network coverage. In [5,6], the sensor nodes are placed in a grid-like manner to ensure coverage and connectivity. A robust and scalable deployment scheme, based on simulated annealing technique for complete coverage is presented in [7]. In [8], Heo and Varshney have proposed a distributed self-deployment algorithm for mobile sensor networks to maximize the coverage and to maintain uniformity in node distribution. Poduri and Sukhatme [9] have proposed a deployment scheme for mobile sensor network to enhance the network coverage with maintaining K-connectivity. In [10], Guo et al. have proposed an adaptive coverage algorithm by considering inner repulsion, random disturbance and boundary contraction to maximize the coverage. By combining the potential field theory and the plate coverage theory, a centralized deployment algorithm called as a Virtual Force Algorithm (VFA) is presented in [11,12]. This VFA cannot quickly converge to a steady state. In [13], the authors proposed a sensor deployment optimization strategy based on Target Involved Virtual Force Algorithm (TIVFA) to improve coverage and detection probability. In [14], Wang et al. have proposed several algorithms that identify existing coverage holes in the network and compute the desired target locations where sensor should move in order to increase the coverage. In [15], the authors developed a decentralized and scalable algorithm based on potential field theory for motion control of mobile sensor networks to cover the maximum area of the free space in minimum time. A localized algorithm for determining whether every point in the service area of the sensor network is covered by at least k sensors is presented in [16]. Voronoidiagram and Delaunay triangulation are used in [17] to estimate the worst and best case coverage in a sensor network. In [18], the authors used Delaunay triangulation, Gabriel graph and relative neighborhood graph to find the path with best coverage. A few excellent surveys on the present state-of-the-art research on sensor network is presented in [19–23]. In [24], the authors have explored> geographic routing in duty-cycled mobile WSNs and proposed two geographic-distance-based connected-k neighborhood (GCKN) sleep scheduling algorithms for geographic routing schemes. In [25], the authors gave necessary and sufficient conditions for 1-coverage and 1-connected wireless sensor grid network. Tian and Georgansa [26] have proved that the communication range is twice of the sensing range is the sufficient condition for complete coverage preservation implies connectivity among active nodes if the original network is connected. The optimal deployment patterns to achieve both full coverage and connectivity for all ranges of Rc/Rs is presented in [27–29]. In [30], the authors proposed a self-deployment mechanism that allows to maintain network connectivity during the deployment of mobile sensor nodes. This mechanism is robust against message losses during deployment. Shen et al. [31] have proposed a grid scan method to calculate coverage rate for arbitrary sensing radius. The main objective of this approach is to provide a better coverage with less nodes. In [32], the authors developed a mechanism to replace failed sensors in a large-scale static sensor networks by using few mobile robots. The goal of this work is to minimize the motion and the messaging overhead. Chen et al. [33] have proposed two novel algorithms named as Improved Virtual Force Algorithm (IVFA) and Exponential Virtual Force Algorithm (EVFA) to improve the performance of traditional VFA. In [34], the authors presented an efficient deployment algorithm named as Self-Deployment by Density Control (SDDC). In this work, virtual force is decided by density at a sensor node and obstacles and the algorithm is not suitable for sparse initial distribution. In [35], Kribi et al. have proposed Dth_Lmax_Serialized_VFA algorithm to enhance coverage and maintain network connectivity of the sensor networks. A Virtual Force directed Co-evolutionary Particle Swarm Optimization (VFCPSO) is presented in [36]. This algorithm is appropriate for small scale application due to its high computation time. Yu et al. [37] have proposed an algorithm base on virtual force and the concept of adjacent relationship of nodes to enhance the coverage rate and reduce the convergence time. A Distributed Virtual Forces Algorithm (DVFA) is proposed in [38] to establish coverage and connectivity. The problem of connectivity optimization in random 3D networks is addressed in [39] where the deployment problem considers the maximization of network connectivity satisfying lifetime constraints. Autonomous mobile robots that deploy a wireless sensor network to be used in disasters is introduced in [40]. In [41], the authors proposed a deployment algorithm for heterogeneous sensor networks based on the circle packing technique to enhance the coverage area. In [42], Xiaoping et al. have analyzed the performance of different virtual force models used in node deployment algorithms.

In this work, an obstacle avoidance VFA is introduced for deployment of both heterogeneous as well as homogeneous mobile sensor nodes over a squared sensing field containing different shape of obstacles.

3. Coverage and sensing model

Coverage is one of the key parameters to evaluate the performance of deployment algorithms [2–9]. According to Poduri and Sukhatme [9], there are three categories of coverage: barrier coverage, target or point coverage, and area coverage. In barrier coverage, sensor nodes have to form a barrier to detect intruders. Target coverage refers to monitoring fixed number of targets in a Region of Interest (ROI). Area coverage means that every point within ROI must be monitored by at least one sensor node or by the joint detection of several sensor nodes. Usually, this coverage is necessary when applications need to monitor the entire area of interest. In general, area coverage [31] means how well the ROI is monitored by the sensor network and is evaluated as in (1).

$$\text{Coverage}(C) = \frac{\cup_{i=1,\ 2,\ \ldots,\ N} A_{si}}{A_{Tot}} \tag{1}$$

Where A_{si} denotes the area covered by the mobile sensor node s_i, N is the number of mobile sensor nodes deployed in ROI and A_{Tot} is the area of the entire ROI.

Sensor models have direct impact on network coverage of WSNs [43]. Sensing models as reported in various literatures can broadly be classified as Binary sensor model and Probabilistic sensing model [10–13,43]. For the purpose of evaluation of our proposed algorithm, we prefer binary sensor model.

3.1. Binary sensor model (BSM)

In most of the existing work, the disk sensing model is used for coverage calculation for its simplicity. According to this model

[11,12,31], an event is detected by a sensor node s_i with a detection probability 1, if the occurrence of the event is within the sensing radius R_s of the sensor node s_i. Otherwise the probability of detection is 0 as given in (2).

$$C_{xy}(p,\ s_i) = \begin{cases} 1, & if\ d(s_i,\ P) \leq R_s \\ 0, & if\ d(s_i,\ P) > R_s \end{cases} \tag{2}$$

Where $d(s_i,\ P) = \sqrt{(x_i - x)^2 + (y_i - y)^2}$ is Euclidean distance between the ith sensor node $s_i(x_i\ ,\ y_i)$ and the event occurring point $P(x, y)$.

3.2. Coverage ratio calculation

For randomly deployed sensor networks, the coverage calculation by geometric analysis is too complicated. Therefore, we adopt a grid scan method [31] to evaluate the coverage ratio. According to this method, the entire ROI is divided into a specified number of uniform grids and each grid is denoted by its center point. The grid is covered if its center point is within the sensing range of a sensor node and the coverage ratio is calculated as in (3).

$$\text{Coverage}(C) = \frac{m}{n} \tag{3}$$

Where, m represents the number of grids covered by the sensor nodes and n is the number of total grids in entire ROI. For binary model, $m = card(\cup_{i=1,2,\ldots N} G_i)$, where G_i denotes the grid points within the sensing range R_s of the $i$thth sensor node. Here, by *card (.)* we indicate cardinality of a set. The accuracy of this method depends upon the size of the grid, the smaller the grid size the more accurate the method.

4. Obstacle Avoidance Virtual Force Algorithm (OAVFA)

The proposed OAVFA is based on the following assumptions. They are: (i) all the sensor nodes have locomotion capability and can move effectively to any direction and any distance within the sensing boundary, (ii) each sensor node has one unique ID, (iii) all sensors are equipped with localization system (i.e. GPS), (iv) every sensor node is able to acquire the relative position of the other sensor nodes within its communication range, (v) all the sensor nodes have circular sensing and communication areas, (vi) the sensing field is a square sized area demarcated with a clear boundary, (vii) the sensing field contains obstacles of different shapes and sizes, (viii) every sensor node is able to detect the shape and position of any obstacles in its sensing range and can calculate the nearest distance from the obstacle by using the time-of-flight method.

The main objective of our proposed OAVFA is not only to maximize the coverage area but also to reduce the moving energy requirement in the presence of different obstacles in ROI. Each sensor node s_i is subjected to an attractive or repulsive force ($\overrightarrow{F_{ij}}$) by its neighbor sensor node s_j, a repulsive force $\overrightarrow{F_{iO_m}}$ by an obstacle O_m, and a repulsive force $\overrightarrow{F_{ib}}$ by sensing field boundaries. Therefore, the net force on a sensor node s_i is evaluated as in (4).

$$\overrightarrow{F_i} = \sum_{j=1,\ j\neq i}^{K} \overrightarrow{F_{ij}} + \sum_{m=1}^{N_O} \overrightarrow{F_{iO_m}} + \overrightarrow{F_{ib}} \tag{4}$$

Where K is the number of neighborhood sensor nodes of s_i; N_O is the number of obstacles in ROI. Depending on the calculated total force $\overrightarrow{F_i}$, the sensor node s_i moves to its new location as given in (5).

$$x_{inew} = x_{iold} + F_{ix};\ \ y_{inew} = y_{iold} + F_{iy} \tag{5}$$

Where x_{iold} and y_{iold} denote the current location of sensor node s_i; x_{inew} and y_{inew} denote the next location of sensor node s_i; F_{ix} and F_{iy} denote the x and y directional components respectively of the displacement s_i goes through as the same is subjected by the force $\overrightarrow{F_i}$. The maximum distance traveled by a sensor node in each iteration is decided by its velocity. So we restrict the upper limit of F_{ix} and F_{iy} by introducing two thresholds Th_x and Th_y.

Fig. 1 shows the flow chart of our proposed algorithm. This localized deployment algorithm is executed at each sensor node s_i and the sensor node ceases its movement if it moves less than a predefined threshold (L_th) for the time duration C_{max}.

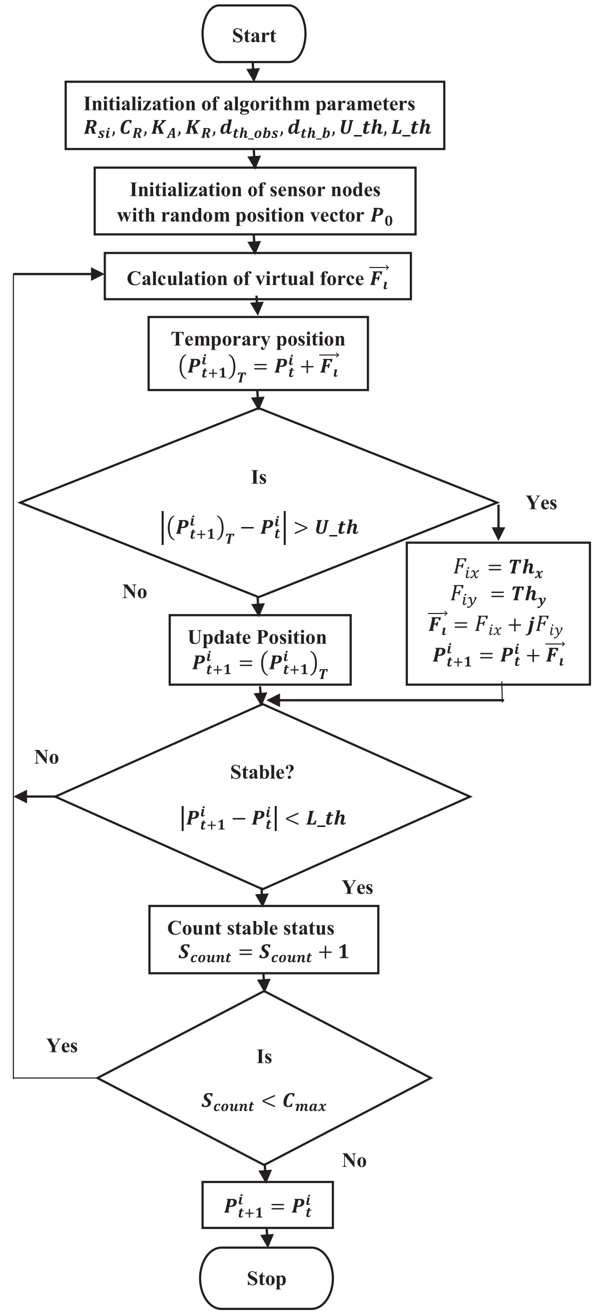

Fig. 1. Obstacle Avoidance Virtual Force Algorithm (OAVFA).

4.1. Virtual force due to sensor node

Consider a network of N sensor nodes $s_1,\ s_2, s_3\ ,\ldots, s_N$ at positions $p_1, p_2, p_3, \ldots, p_N$ with sensing radius $R_{s1}, R_{s2}, R_{s3}, \ldots, R_{sN}$ respectively and each sensor node is defined by its communication range C_R. Let d_{ij} represent the Euclidean distance between the sensor nodes s_i and s_j, i.e. $d_{ij} = \|p_i - p_j\|$ and the force exerted on s_i by the neighbor sensor node s_j be denoted by $\overrightarrow{F_{ij}}$. The force model is given in 6).

$$\overrightarrow{F_{ij}} = \begin{cases} 0 & if\ d_{ij} > C_R \\ \left(K_A\left(d_{ij} - d_{th}^{ij}\right)\right)\left(\frac{p_j - p_i}{d_{ij}}\right) & if\ C_R \geq d_{ij} > d_{th}^{ij} \\ 0 & if\ d_{ij} = d_{th}^{ij} \\ \left(K_R\left(d_{th}^{ij} - d_{ij}\right)\right)\left(\frac{p_i - p_j}{d_{ij}}\right) & if\ d_{ij} < d_{th}^{ij} \end{cases} \tag{6}$$

Where K_A and K_R are the force coefficients. Usually $K_A \leq K_R$. The threshold distance d_{th}^{ij}controls the overlapping degree between the sensor nodes s_i and s_j and for our proposed model $d_{th}^{ij} = \frac{\sqrt{3}}{2}(R_{si} + R_{sj})$. In case of homogeneous sensor network, the sensing range is identical for all sensor nodes i.e. $R_{s1} = R_{s2=} \ldots R_{sN} = R_s$ and the threshold distance $d_{th} = \sqrt{3}R_s$.

4.2. Force model of obstacle on sensor

The obstacles such as walls or buildings exert repulsive forces on a sensor node. Let d_{iO_j} is the shortest distance between the sensor node s_i and the obstacle O_j and (x_{oj}, y_{oj}) is the nearest point in the obstacle O_j from sensor node s_i. If the distance d_{iO_j} is less than a pre-defined threshold distance d_{th}_obs, a repulsive force is exerted by the obstacle O_j on sensor node s_i and the force is computed as in (7).

$$\overrightarrow{F_{iO_j}} = \begin{cases} 0 & if\ d_{iO_j} \geq \ (d_{th}\_obs) \\ \left(K_{R1}\ (d_{th}\_obs - d_{iO_j}), \alpha_{iO_j} + \pi\right) & if\ d_{iO_j} < \ (d_{th}\_obs) \end{cases} \tag{7}$$

Where K_{R1} is a constant parameter that represents the strength of the repulsive force.

4.3. Boundary force on sensor

The boundary forces on the sensor reduce the unwanted coverage outside the ROI. The boundaries of sensing field exert repulsive forces on a sensor. Let d_{ib} is the perpendicular distance between the sensor node s_i and the sensing field boundary. If the distance d_{ib} is less than a pre-defined threshold distance d_{th}_b, a repulsive force is exerted by the boundary on sensor node s_i and the force is computed as in (8)

$$\overrightarrow{F_{ib}} = \begin{cases} 0 & if\ \ d_{ib} \geq \ (d_{th}\_b) \\ (K_{R2}(d_{th}\_b - d_{ib}), \alpha_{ib} + \pi) & if\ \ d_{ib} < \ (d_{th}\_b) \end{cases} \tag{8}$$

In a squared area, the boundary forces will be there due to the four boundaries surrounding the ROI. Thus $\overrightarrow{F_{ib}}$ is the combined force from all boundaries as given in (9).

$$\overrightarrow{F_{ib}} = \overrightarrow{F_{ib}^{x_1}} + \overrightarrow{F_{ib}^{x_2}} + \overrightarrow{F_{ib}^{y_1}} + \overrightarrow{F_{ib}^{y_2}} \tag{9}$$

The above virtual forces guide the mobile sensor nodes to enhance the area coverage while maintaining connectivity, prevent the sensor nodes from moving out of sensing field boundary, and avoid the obstacles. In OAVFA, each node stops its movement when it has reached its stable position.

In this paper, the performances of distributed deployment algorithms are evaluated by considering two aspects: coverage ratio and moving energy consumption. Coverage ratio is the ratio of the number of grid points that are not in obstacle and have a detection probability of 1 to the total number of grid points in ROI that are not in obstacles and is evaluated as in (3). Moving energy consumption means the energy required for movement of sensor nodes. In this work, the moving energy consumption is considered as the average moving distance of all sensor nodes in each step and is calculated as in (10).

$$D_{avg} = \frac{\sum_{i=1}^{N}\sqrt{\left(x(i)_{new} - x(i)_{old}\right)^2 + \left(y(i)_{new} - y(i)_{old}\right)^2}}{N} \tag{10}$$

Table 1
Simulation parameters.

Parameters	Value
Field size	100 m × 100 m
Grid size	1 m × 1 m
Max. velocity of sensor node	0.5 m/s
K_A	0.001
K_R	0.2
K_{R1}	0.8
K_{R2}	0.8
U_th	0.5
L_th	0.001
C_{max}	10
Max_iteration	300

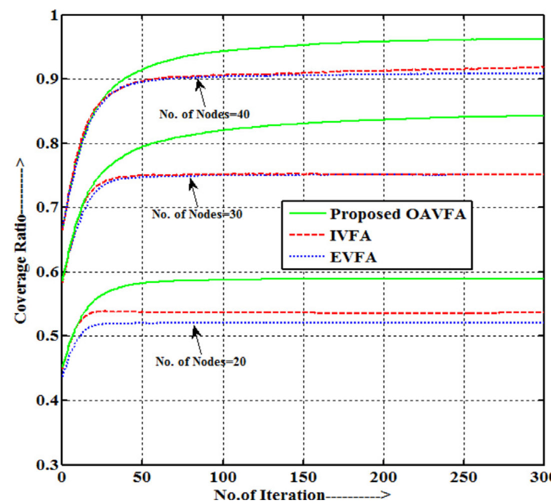

Fig. 2. Binary coverage ratio vs. no. of iterations.

5. Simulation results

We have implemented the deployment algorithms in MATLAB environment to demonstrate their performance. In our simulation, the sensor nodes are initially deployed at random over a 100 m by 100 m squared sensing field and grid scan method is used for evaluation of network coverage. The sensing field is treated as 100 by 100 grids when we calculate the coverage. In this paper we assume that the maximum velocity of each mobile sensor node is 0.5 m/s. For simulation, we set the maximum distance that a sensor node can move in each iteration as 0.5 m. The parameters used for simulation are given in Table 1.

5.1. Simulation using homogeneous sensors

The simulation results obtained using homogeneous mobile sensor nodes having sensing range 10 m and communication range 20 m is presented in this section. Here, we use statistical methods to analyze the performance of deployment algorithms. In our simulation, 100 different random initial deployments are applied to each deployment algorithm. The parameters used for simulation are given in Tables 1 and 2. Fig. 2 shows the average final binary coverage ratio vs. iterations for IVFA [33], EVFA [33], and our proposed OAVFA without any obstacles when number sensors deployed in ROI is 20, 30 and 40.

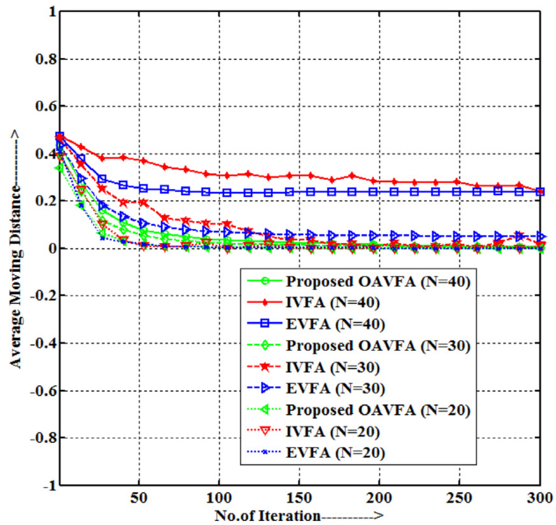

Fig. 3. Average moving distance vs. no. of iterations.

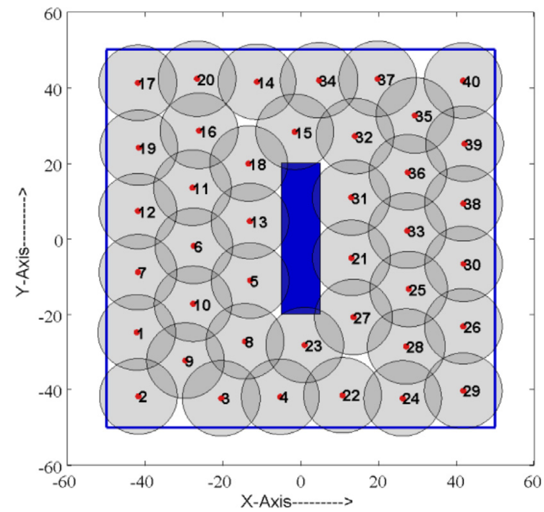

Fig. 5. Final deployment with coverage rate 97.75%.

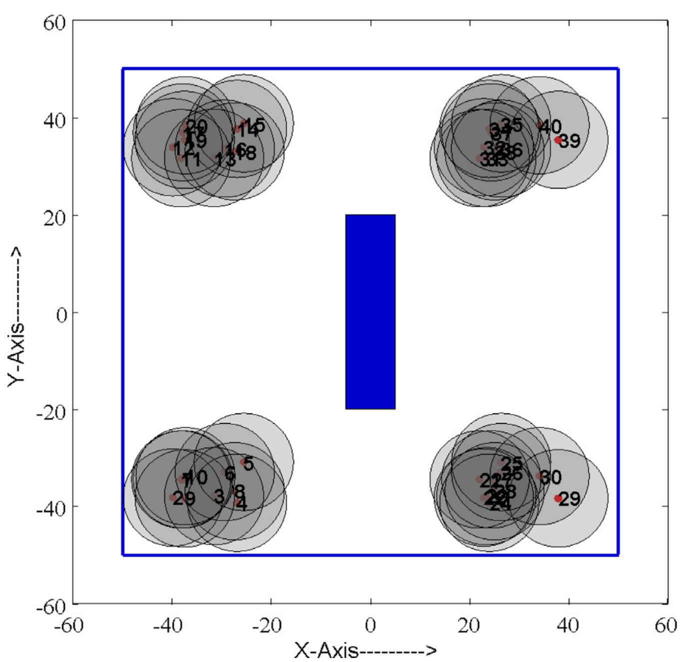

Fig. 4. Initial sensor position with coverage rate 31.61%.

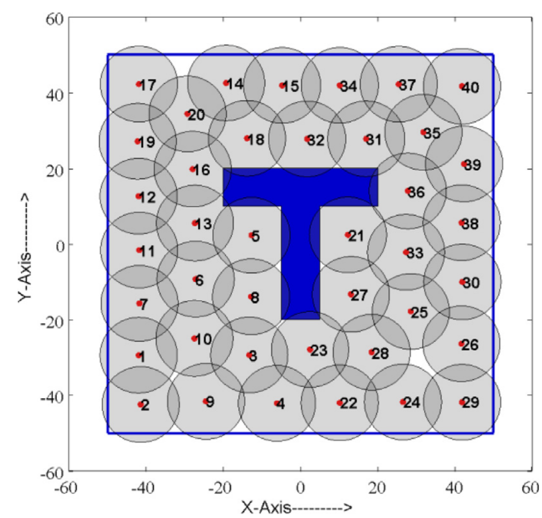

Fig. 6. Final deployment with coverage rate 98.29%.

Table 2
Simulation parameters for homogeneous sensor.

Parameters	Value
Sensing Range (R_s)	10 m
Communication Range ($C_R = 2 \times R_s$)	20 m
Threshold distance ($d_{th} = \sqrt{3}R_s$)	17.32 m
$d_{th\_obs} = \sqrt{3}R_s/2$	8.66 m
$d_{th\_d} = \sqrt{3}R_s/2$	8.66 m

From Fig. 2 it is clear that the coverage ratio due to OAVFA is higher than the other two approaches. Fig. 3 shows the average moving distance of sensor nodes in each step. The average moving energy consumption of virtual force algorithms decreases and ours converge very fast as compare to other two algorithms.

The performance of IVFA, EVFA and OAVFA on coverage rate and convergence time for three different network sizes with number of sensor nodes $N = 20$, 30 and 40 is given in Table 3. We observe that OAVFA attain a higher coverage rate compare to IVFA and EVFA for all three cases. For IVFA and EVFA, in the case of $N = 40$ and 30, some nodes are still subjected to repulsive or attractive force and move continuously even when the coverage rate remains constant. For OAVFA, the algorithm converge very well after 80, 200 and 220 iterations, respectively.

We also simulate OAVFA in presence of different shapes of obstacle at the central area of ROI. Initially, 40 homogeneous mobile sensor nodes having sensing radius 10 are split into four groups and randomly deployed at the four corners of the sensing field as shown in Fig. 4. From Figs. 5–11 illustrate the final sensor locations after execution of proposed OAVFA.

From above results, it is clear that at the end of final deployment, no mobile sensor node is outside the ROI and the sensor nodes are self-deployed with avoidance of obstacle to cover the whole sensing field and also maintain the connectivity. The average final binary coverage rate vs. number of iterations with and without obstacles for 100 different initial deployments is shown in Fig. 12. It appears that the coverage rate is as good as with and without the presence of an obstacle in ROI.

Table 3
Performance summery.

Parameters	IVFA			EVFA			OAVFA		
N	40	30	20	40	30	20	40	30	20
Coverage Rate (%)	91.8	75.1	53.6	90.7	75.1	52	96.2	84.2	60
No. of iterations to achieve steady state	>300	>300	150	>300	>300	90	220	200	80

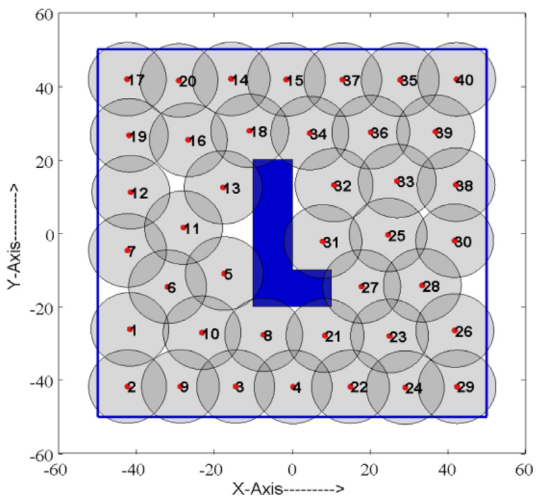

Fig. 7. Final deployment with coverage rate 97.19%.

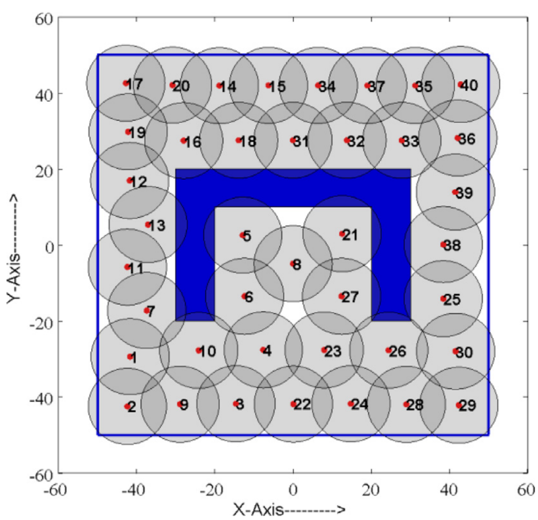

Fig. 8. Final deployment with coverage rate 97.09%.

5.2. Simulation using heterogeneous sensors

The simulation results due to heterogeneous mobile sensors are presented in this section. Initially, the heterogeneous mobile sensors are randomly deployed in a 100 m by 100 m squared sensing field containing different shape of obstacles. We set maximum sensing range limit is 10 and communication range of each sensor node is 20 (i.e. $C_R = 2 \times$ maximum sensing range limit) and minimum sensing range limit is 6. The parameters used for simulation are given in Tables 1 and 4. Fig. 13 shows the average final binary coverage ratio vs. iterations for IVFA [33], EVFA [33], and our proposed OAVFA without any obstacles when number sensor deployed in ROI is 60, 40 and 20.

Fig. 13, indicates that, our proposed algorithm has better coverage than that of other two VFA approaches. The average moving distance of sensor nodes in each step is shown in Fig. 14. The average moving distance decreases for all three deployment algorithms, but ours converge faster. The performance of IVFA, EVFA and OAVFA on coverage rate for three different network sizes with number of sensor nodes N = 20, 40 and 60 is given in Table 5. We observe that OAVFA attain a higher coverage rate compare to IVFA and EVFA for all three cases. For IVFA and EVFA, in the case of N = 20, 40, and 60 some nodes are still subjected to repulsive or at-

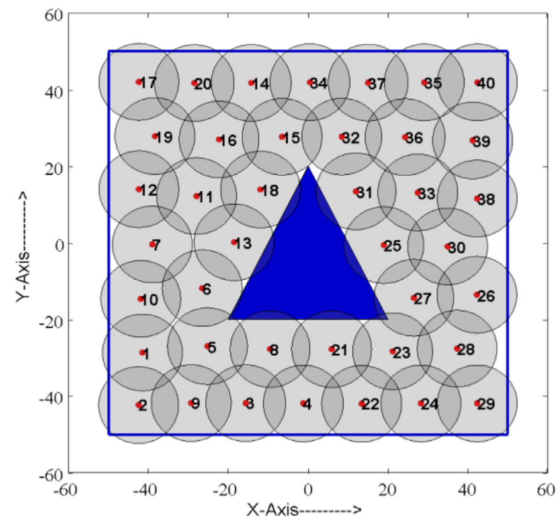

Fig. 9. Final deployment with coverage rate 97.86%.

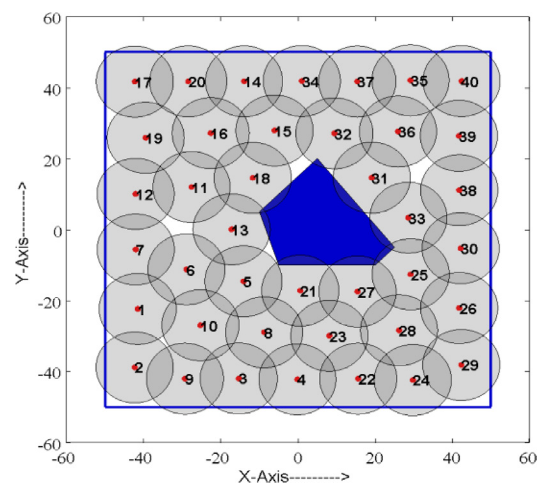

Fig. 10. Final deployment with coverage rate 97.52%.

Table 4
Simulation parameters for heterogeneous sensor.

Parameters	Value
Sensing Range limit (R_{si})	6 m–10 m
Communication Range ($C_R = 2 \times \max(R_{si})$)	20 m
Threshold distance (d_{th}^{ij})	$\frac{\sqrt{3}}{2}(R_{si} + R_{sj})$
$d_{th\_obs}(s_i)$	$\sqrt{3}R_{si}/2$
$d_{th\_b}(s_i)$	$\sqrt{3}R_{si}/2$

Table 5
Performance summery.

Parameters	IVFA			EVFA			OAVFA		
N	60	40	20	60	40	20	60	40	20
Coverage Rate (%)	96.1	81.1	42.6	94.7	80.9	43	98.5	85	43.6

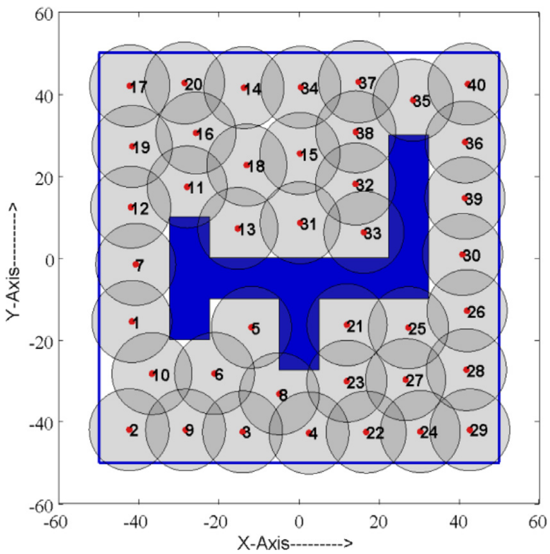

Fig. 11. Final deployment with coverage rate 98.34%.

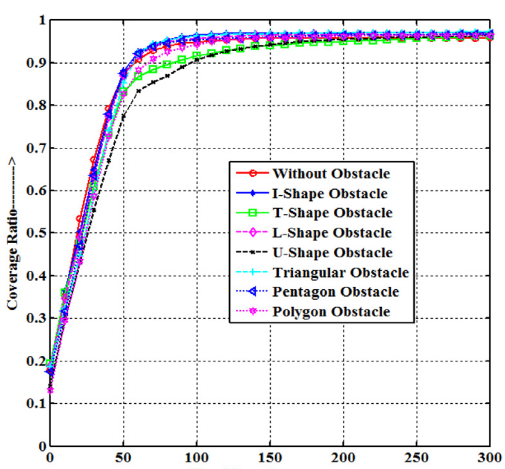

Fig. 12. Coverage rate with and without obstacles.

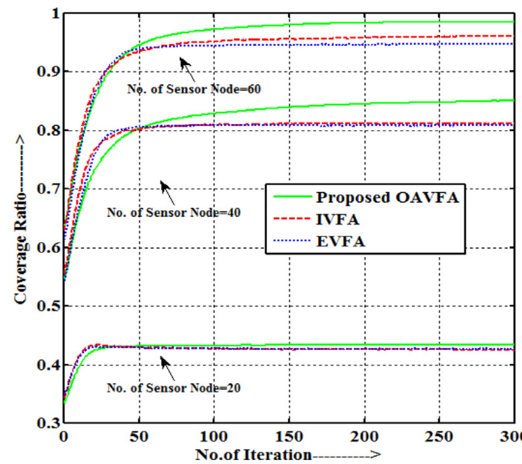

Fig. 13. Binary coverage ratio vs. no. of iterations.

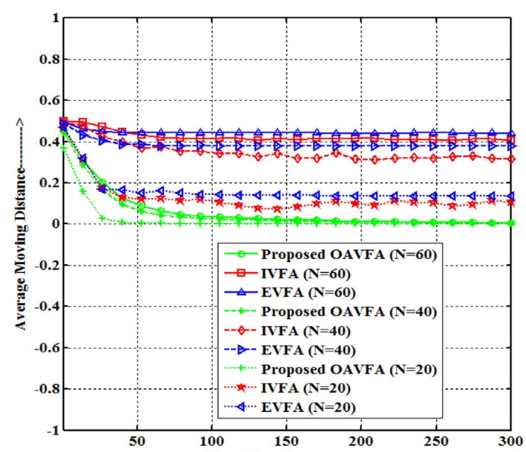

Fig. 14. Average moving distance vs. no. of iteration.

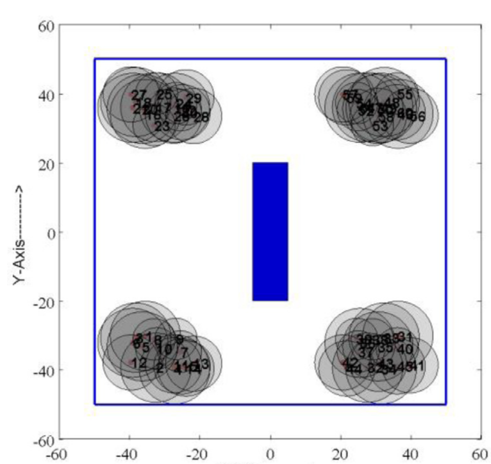

Fig. 15. Initial deployment with coverage rate 29.94%.

tractive force and move continuously even when the coverage rate remains constant. For OAVFA, the algorithm converge very well after 70, 220 and 250 iterations, respectively

To demonstrate the performance of proposed OAVFA with different obstacle shapes we have simulated our approach in a 100 m by 100 m squared sensing field cover with a clear boundary with different obstacle shapes at the central area of ROI. Fig. 15 illustrates the initial random deployment of 60 heterogeneous sensor nodes at four corners of ROI in the presence of I-shape obstacle and Figs. 16–22 illustrate the final position of sensor nodes after 300 iterations in the presence of different shape of obstacles in ROI.

From above results, it is clear that at the end of final deployment, no mobile sensor node lies outside the ROI. The sensor nodes are self-deployed with avoidance of obstacle to cover the whole sensing field and the connectivity is also maintained. We

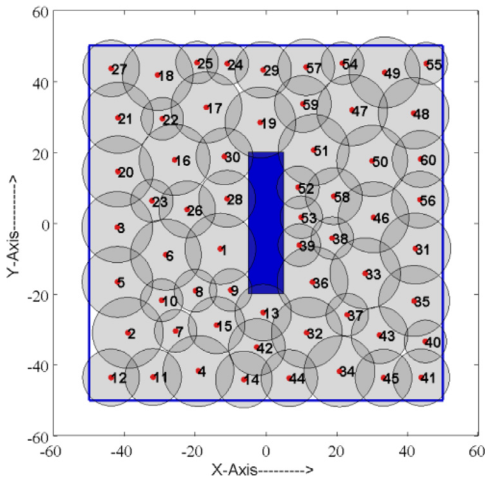

Fig. 16. Final deployment with coverage rate 99.14%.

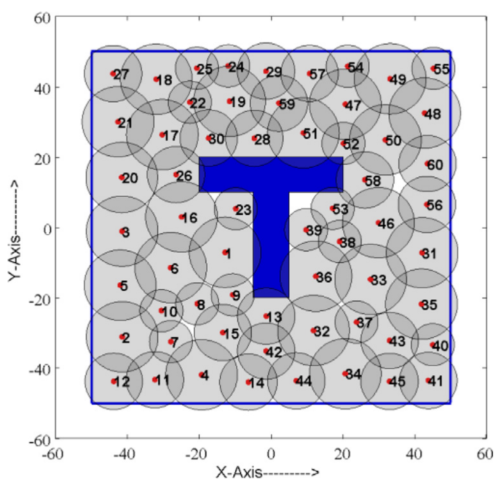

Fig. 17. Final deployment with coverage rate 98.7%.

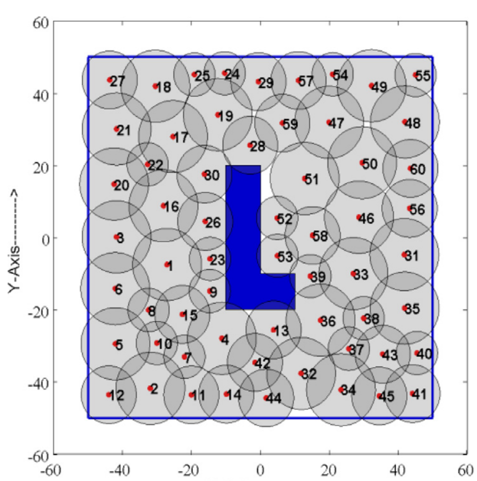

Fig. 18. Final deployment with coverage rate 98.92%.

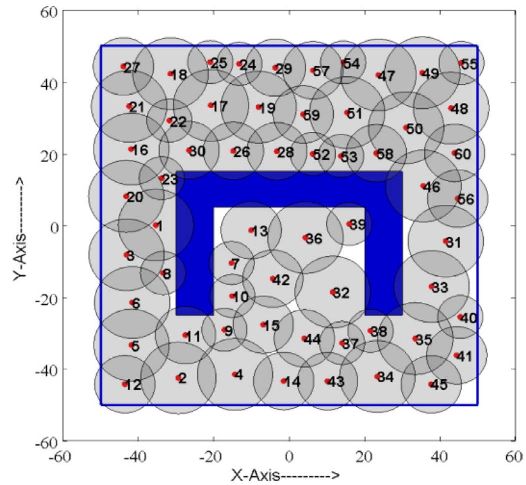

Fig. 19. Final deployment with coverage rate 97.98%.

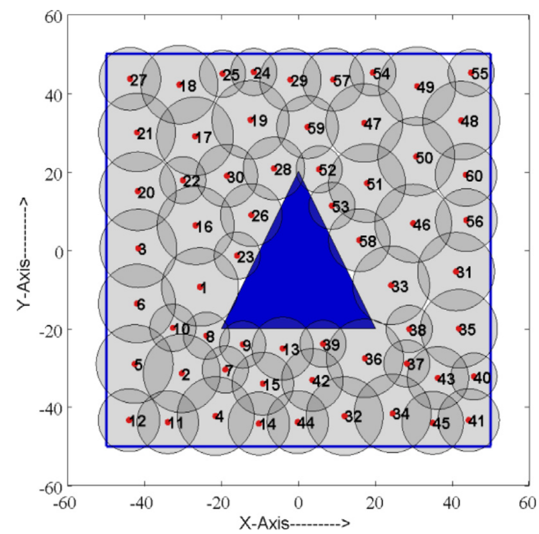

Fig. 20. Final deployment with coverage rate 99.38%.

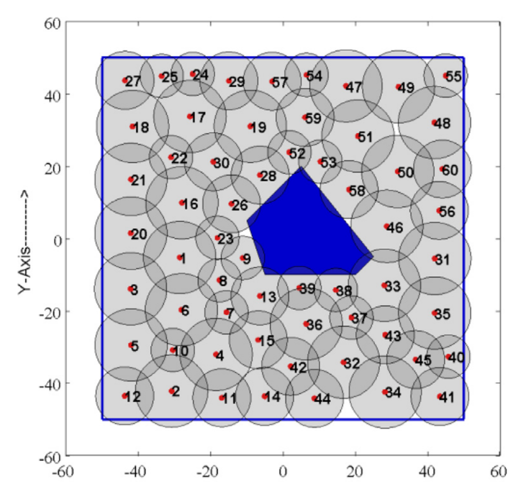

Fig. 21. Final deployment with coverage rate 99.09%.

studied the impact of the shape of the obstacles on the coverage rate. The average final binary coverage rate vs. number of iterations with and without obstacles for 100 different initial deployments is shown in Fig. 23. It appears that the coverage rate is as good as with and without the presence of an obstacle in ROI

6. Conclusion

In this paper, we propose a localized self- deployment scheme called OAVFA for homogeneous as well as heterogeneous mobile sensor networks with random initial distribution. This algorithm works well in the scenarios of the random initial distribution of

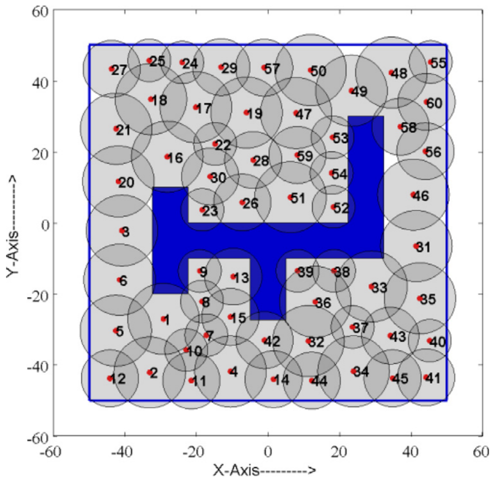

Fig. 22. Final deployment with coverage rate 98.96%.

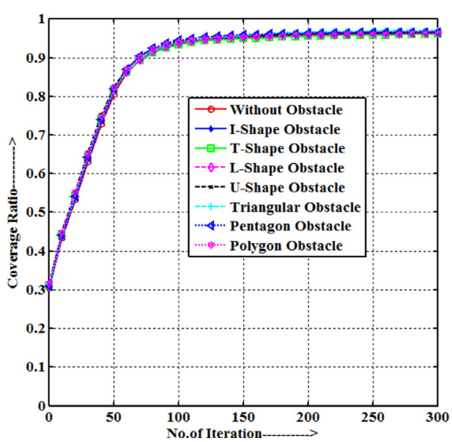

Fig. 23. Binary coverage with and without obstacles.

mobile sensor nodes to maximize the area coverage and minimize the moving energy requirement in the presence of obstacles while maintaining connectivity. To prevent the sensor nodes from moving out of sensing field boundary, we consider a repulsive force exerted by sensing field boundary. We also add repulsive force exerted by obstacles to avoid the presence of obstacles in ROI. Simulation results demonstrate that the proposed approach provides better performance than IVFA and EVFA for deployment of homogeneous as well as heterogeneous sensor nodes in a squared sensing field with and without the obstacles.

References

[1] K. Sohraby, D. Minoli, T.F. Znati, Wireless Sensor Networks: Technology, Protocol and Applications, Wiley-Interscience, 2007.
[2] A. Howard, M. Mataric, Cover me! A self-deployment algorithm for mobile sensor networks, in: Proceedings of 2002 IEEE International Conference on Robotics and Automation, ICRA'02, Washington, DC, May, 2002, pp. 80–91.
[3] A. Howard, M. Mataric, G. Sukhatme, An incremental self-deployment algorithm for mobile sensor networks, Auton. Robots Spec. Issue Intell. Embed. Syst. 13 (2) (2002) 113–126.
[4] A. Howard, M. Mataric, G. Sukhatme, Mobile sensor network deployment using potential fields: A distributed scalable solution to the area coverage problem, in: Proceedings of the Sixth International Symposium on Distributed Autonomous Robotic Systems, DARS'02, Fukuoka, Japan, June, 2002, pp. 299–308.
[5] K. Chakrabarty, S.S. Iyengar, H. Qi, E. Cho, Grid coverage for surveillance and target location in distributed sensor networks, IEEE Trans. Comput. 51 (12) (2002) 1448–1453.
[6] S.S. Dhillon, K. Chakrabarty, S.S. Iyengar, Sensor placement for grid coverage under imprecise detections, in: Proceedings of the Fifteenth International Conference on Information Fusion, July, 2002, pp. 1581–1587.
[7] F.Y.S. Lin, P.L. Chiu, A near-optimal sensor placement algorithm to achieve complete coverage-discrimination in sensor networks, IEEE Commun. Lett. 9 (2005) 43–45.
[8] N. Heo, P.K. Varshney, A distributed self-spreading algorithm for mobile wireless sensor networks, in: Proceedings of the IEEE Wireless Communications and Networking Conference, WCNC'03, New Orleans, LA, March, 2003, pp. 1597–1602.
[9] S. Poduri, S. Sukhatme, Constrained coverage for mobile sensor networks, in: Proceedings of the IEEE International Conference on Robotics and Automation, 2004, pp. 165–172.
[10] P. Guo, G. Zhu, L. Fang, An adaptive coverage algorithm for large-scale mobile sensor networks, in: Proceedings of the 2006 Ubiquitous Intelligence and Computing, Springer Verlag, Berlin Heidelberg, 2006, pp. 468–477.
[11] Y. Zou, K. Chakrabarty, Sensor deployment and target localization based on virtual forces, in: Proceedings of the Twenty-second International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'03), 2003, pp. 1293–1303.
[12] Y. Zou, K. Chakrabarty, Sensor deployment and target localization in distributed sensor networks, IEEE Trans. Embed. Comput. Syst. 3 (1) (2004) 61–91.
[13] S. Li, X. Congfu, W. Pan, Y. Pan, Sensor deployment optimization for detecting maneuvering targets, in: Proceedings of Eighth International Conference on the Information Fusion, 2005, pp. 1629–1635.
[14] G. Wang, G. Cao, T.L. Porta, Movement-assisted sensor deployment, IEEE Trans. Mob. Comput. 5 (6) (2006) 640–652.
[15] G.A. Nighojkar, J.M. Watkins, J.M. Esposito, Maximizing the area coverage in constrained environment for mobile sensor network, in: Proceeding of the Second Annual Symposium on Graduate Research and Scholarly Project (GRASP), Wichita State University, 2006, pp. 154–155.
[16] C.F. Huang, Y.C. Tseng, The coverage problem in a wireless sensor network, in: Proceedings of the Second ACM International Conference on Wireless Sensor Networks and Applications, ACM Press, New York, NY, 2003, pp. 115–121.
[17] S. Megerian, F. Koushanfar, M. Potkonjak, M. Srivastava, Worst and best-case coverage in sensor networks, IEEE Trans. Mob. Comput. 4 (1) (2005) 84–92.
[18] X. Li, P. Wan, O. Frieder, Coverage in wireless ad hoc sensor networks, IEEE Trans. Comput. 52 (6) (2003) 753–763.
[19] Z. Bojkovic, B. Bakmaz, A survey on wireless sensor networks deployment, WSEAS Trans. Commun. 7 (12) (2008) 1172–1181.
[20] M. Younis, K. Akkaya, Strategies and techniques for node placement in wireless sensor networks: a survey, J. Ad Hoc Netw. 6 (4) (2008) 621–655.
[21] J. Yick, B. Mukherjee, D. Ghosal, Wireless sensor network survey, J. Comput. Netw. 52 (12) (2008) 2292–2330.
[22] B. Wang, Coverage problems in sensor networks: A survey, ACM Comput. Surv. 43 (4) (2011) 1–53.
[23] C. Zhu, C. Zheng, L. Shu, G. Han, A survey on coverage and connectivity issues in wireless sensor networks, J. Netw. Comput. Appl. 35 (2) (2012) 619–632.
[24] C. Zhu, L.T. Yang, L. Shu, C.M. Leung, J.P.C. Rodrigues, L. Wang, Sleep scheduling for geographic routing in duty-cycled mobile sensor networks, IEEE Trans. Ind. Electron. 61 (11) (2014) 6346–6355.
[25] S. Shakkottai, R. Srikant, N. Shroff, Unreliable sensor grids: coverage, connectivity and diameter, in: Proceedings of the Twenty-second International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'03), 2003, pp. 1073–1083.
[26] Di. Tian, N.D. Georganas, Connectivity maintenance and coverage preservation in WSNs, J. Ad Hoc Netw. 3 (2005) 744–761.
[27] X. Bai, S. Kumar, D. Xuan, Z. Yun, T.H. Lai, Deploying wireless sensors to achieve both coverage and connectivity, in: Proceedings of the Seventh ACM International Symposium on Mobile Ad Hoc Networking and Computing, MobiHoc'06, Florence, Italy, May, 2006, pp. 131–142.
[28] X. Bai, D. Xuan, Z. Yun, T.H. Laiand, W. Jia, Complete optimal deployment patterns for full-coverage and k-connectivity (k ≤6) wireless sensor networks, in: Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing, MobiHoc'08, 2008, pp. 401–410.
[29] X. Bai, Z. Yun, D. Xuan, T.H. Lai, W. Jia, Optimal patterns for four-connectivity and full coverage in wireless sensor networks, IEEE Trans. Mob. Comput. 9 (3) (2010) 435–448.
[30] T. Razafindralambo, D. Simplot, Connectivity preservation and coverage schemes for wireless sensor networks, IEEE Trans. Autom. Control 56 (10) (2011) 2418–2428.
[31] X. Shen, J. Chen, Z. Wang, Y. Sun, Grid Scan: A simple and effective approach for coverage issue in wireless sensor networks, in: Proceedings of the IEEE International Conference on Communication, June, 2006, pp. 3480–3484.
[32] Y. Mei, C. Xian, S. Das, Y.C. Hu, Y.H. Lu, Sensor replacement using mobile robots, J. Comput. Commun. 30 (2007) 2615–2626.
[33] J. Chen, S. Li, Y. Sun, Novel deployment schemes for mobile sensor networks, Sensors 7 (11) (2007) 2907–2919.
[34] R. Chang, S. Wang, Self-deployment by density control in sensor networks, IEEE Trans. Veh. Technol. 57 (3) (2008) 1745–1755.
[35] F. Kribi, P. Minet, A. Laouiti, Redeploying mobile wireless sensor networks with virtual forces, in: Proceedings of the Second IFIP Conference on Wireless Days, (WD'09), Piscataway, NJ, USA, 2009, pp. 254–259.

[36] X. Wang, X. Sun, S. Wang, Y. Wang, Distributed strategy for sensing deployment in wireless sensor networks, in: Proceedings of the International Symposium on Communications and Information Technologies (ISCIT), 2010, pp. 64–69.
[37] X. Yu, W. Huang, J. Lan, X. Qian, A novel virtual force approach for node deployment in wireless sensor network, in: Proceedings of the Eighth International Conference on Distributed Computing in Sensor Systems (DCOSS'12), 2012, pp. 359–363.
[38] S. Mahfoudh, I. Khoufi, P. Minet, A. Laouiti, Relocation of mobile wireless sensors in the presence of obstacles, in: Proceedings of the International Conference on Telecommunications (ICT), Maroc, 2013, pp. 1–5.
[39] F.M. Al-Turjman, H.S. Hassanein, M.A. Ibnkahla, Efficient deployment of wireless sensor networks targeting environment monitoring applications, J. Comput. Commun. 36 (2) (2013) 135–148.
[40] G. Tuna, V.C. Gungor, K. Gulez, An autonomous wireless sensor network deployment system using mobile robots for human existence detection in case of disasters, J. Ad Hoc Netw. 13 (2014) 54–68.
[41] M. Lam, Y. Liu, Heterogeneous sensor network deployment using circle packing, in: Proceedings of the IEEE International Conference on Robotics and Automation, April, 2007, pp. 4442–4447.
[42] R. Xiaoping, C. Zixing, L. Zhao, W. Wuyi, Performance analysis of virtual force models in node deployment algorithm of wireless sensor network, Adv. Intell. Soft Comput. 138 (2012) 1–9.
[43] A. Hossain, S. Chakrabarti, P.K. Biswas, Impact of sensing model on wireless sensor network coverage, IET Wirel. Sens. Syst. 2 (3) (2012) 272–281.

Mrutyunjay Rout received his B.E. degree in Electronics and Instrumentation Engineering from Berhampur University, Orissa, India, with first class honors in 2002 and the M.Tech. degree in Measurement and Instrumentation from Indian Institute of Technology Roorkee (IITR), Uttarakhand, India, in 2010 with a gold medal. He is currently pursuing his Ph.D. degree in the Department of Electronics and Electrical Communication Engineering, Indian Institute of Technology Kharagpur (IITKGP), West Bengal, India. His current research interests include mobile sensor networks and smart sensors.

Rajarshi Roy received the B.E. degree in electronics and telecommunication from Jadavpur University, Kolkata, India, with first class honors in 1992 and the M.Sc. (Engg) degree in electrical communication engineering from the Indian institute of Science, Bangalore, Karnataka, India in 1995. He received the Ph.D. degree in electrical engineering with a specialization in networking from Polytechnic University, Brooklyn, New York, in 2001 (Now known as New York University Tandon School of Engineering). In July 2002, he joined with the Department of Electronics and Electrical Communication Engineering, IIT Kharagpur, India, as an assistant professor. He was promoted to associate professor rank in year 2010. Prior to this, he worked for the Performance Analysis Group of the Advanced Development Department of Comverse, Wakefield, Massachusetts, as a performance analyst software engineer and as an engineer for Lucent Technologies India Development Center in Bangalore, India. He also worked in the Applied Statistics Unit of the Indian Statistical Institute (Fall 2001), Kolkata, India, as a visiting scientist, as an academic visitor for Comm. lab, Helsinki University of Technology, Espoo, Helsinki, Finland (Fall 2004), as a summer intern in Bell labs, Holmdel, NJ (Summer 1997) and as an adjunct teacher in Polytechnic Brooklyn (Summer 2000). His current research interests include communication networks, network coding, cooperation in communication and control, network science, and control, optimization, resource allocation, and performance evaluation of networked complex systems.