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A local location-based self-adjusting deployment algorithm for MSN

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Abstract. Aimed at maximizing coverage area and minimizing coverage gaps, we propose a deployment algorithm named local location based self-adjusting deployment (LLSAD) for mobile sensor network. Based on the analysis of the theory on optimal nodes layout with full coverage, a rule of sensors adjusting and location update is established. According to the rule, the sensor nodes can move close to the position of layout with full coverage in task region. The LLSAD algorithm realizes local optimal coverage by updating the local nodes' location to achieve required coverage. The simulation results have demonstrated that LLSAD can rapidly improve the coverage and achieve convergence under several different initial deployments to provide guarantee of coverage (quality of service-QoS). Moreover, sensor nodes do not need to maintain global sensor nodes' location data. It is highly applicable for sensor network, which has limited resources.

Key words. Local location, self-adjusting deployment, mobile sensor network, coverage QoS.

1. Introduction

Wireless Sensor Network (WSN) consists of many sensor nodes, which have capabilities of perceiving, computing and communicating. As an sensing infrastructure of Cyber Physical Systems (CPS) [1], WSN relies on all sensor nodes to cooperatively monitor physical world and gather the conditions of things. Coverage performance is a crucial quality of service (QoS) metric of WSN, which is the capacity of perceiving and collecting the status information of monitored objects in task region. Node deployment has much influence on the coverage performance. For a task in a specific region, deployment algorithm determines the number of nodes as well as their positions, to meet the application's requirement of coverage quality.

With the increasing popularization of CPS, WSN has been widely used in several fields including some fields where human access rarely, such as forewarning of forest fire, volcano monitoring, wetland monitoring, etc. In generally, a large and

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redundant number of nodes are deployed randomly in task regions, to obtain a high coverage rate. However, it is still hard to guarantee the nodes distributed uniformly and meet the applications' coverage requirements. Thus, the nodes need redeployment [2]. In addition, some nodes exhaust will break the network structure and decrease coverage capacity [3]. Redeployment could optimize the layout of the remaining alive nodes to maintain a good coverage rate. Mobile sensor nodes [4, 5] can update their position dynamically to meet coverage requirement. What is more, mobile WSN can track the change of the target events' area and redeploy nodes correspondingly, such as pollution diffusion, fire spread monitoring, etc. Hence, the deployment based on mobility is a key support for QoS guarantee in WSN.

In this paper, we propose a self-adjusting deployment algorithm LLSAD for Mobile Sensor Network (MSN). Each sensor node updates position based on the layout with full coverage in task region that references greedy ideas, which adjusts the distance to its adjacent neighbors to achieve required coverage in global. It improves the coverage rate rapidly with no need to exchange and maintain global sensor position information.

2. Related works

One crucial deployment mechanism of sensor nodes is virtual force algorithm (VFA), which is proposed in [6]. Each pair of nodes exerts positive force if they are too far apart from each other in VFA, or exerts negative forces if they are too close. A node will move unless the net force from all neighbors is not zero. By using a force-directed approach, VFA improves the coverage provided by an initial random placement. An improvement of VFA [7] is used to deploy sensors in a region with obstacles and guarantee connectivity. However, the algorithm in [7] did not take into account redeployment of residue sensor node in operation. Some mobile sensor nodes are added to a static sensor network to improve performance by moving them to locations of a coverage hole based on the VFA [8]. Besides, there are some variations [9, 10] of VFA that are presented for mobile sensor network. Although the algorithms-based virtual force improves coverage in sensor network, the collisions of nodes occurs occasionally due to varied direction of net force and indefinite destination position. Moreover, the number of nodes needed to achieve required coverage in theoretical is not taken into account in the algorithms and evaluations are operated in some experienced and random situations.

Many redeployment strategies based on Voronoi diagram are proposed to optimize coverage of sensor nodes. Three algorithms of VEC, VOR and Minimax are presented in [11] to relocate sensors to build a Voronoi diagram and reach a high coverage rate. VEC can disperse dense nodes, VOR and Minimax are used to repair coverage hole. By calling Minimax and calculating Maxim-Edge of Voronoi directly, VEDGE [12] can enhance coverage at a high cost of computation. CBS [13] is a deployment algorithm which transforms the coverage problem of a network into the optimization problem of Voronoi polygon corresponding to each node. CBS algorithm has a low complexity, but there exist some small coverage holes inside the Voronoi polygons. The deployment algorithms-based Vonoroi polygon can determine exact position of each node on the premise of all nodes' location data. The cost of exchanging location data is too high to afford in a sensor network without power harvesting.

There are other strategies [14, 15] that exploit mobility of sensor to improve coverage. A technique for k-overage is proposed [14] in a grid-divided network, in which a few weak-mobility sensors are controlled to migrate from a grid to the adjacent one and collaborate with pre-placed static sensors to realize k-coverage. An algorithm based on the divide-and-conquer approach is proposed in [15]. By dividing task region into sub-regions and selecting the minimum connected sensor cover set for each sub-region considering the energy, a mobility assisted minimum connected sensor cover is achieved. It can significantly increase the capability of a remainder network with loss of connectivity as failure of some sensors. The methods above provide a fixed degree of coverage with no adaptive reconfiguration, in which the mobility of sensors is weak.

Based on the theoretical analysis on number and layout of nodes with full coverage, our LLSAD algorithm adopts self-adjusting to meet required coverage relying on the locations of sensors.

3. System model

3.1. Network and coverage model

In generally, WSN can be described as an undirected graph $G = (V, E)$, where V is the set of sensor nodes deployed in monitoring region, and E is the set of the links between two adjacent nodes. Assume that all nodes have the same communication radius R and sense radius r. It requires network keep connectivity when the nodes deployment is done, which means there are no isolated nodes. According to literature [16], if the sensor nodes' communication radius R is twice of sense radius r, the deployed nodes can fully cover the monitoring convex region and communicate with their neighbor nodes. Assuming n nodes are deployed in a monitoring region A, some definitions are as follows:

3.1.1. Neighbor set. The neighbor set of node v_i consists of all nodes located in its communication range. This is defined as follows:

$$N(v_i) = \{v_j|\mathrm{dist}\,(v_i, v_j) \le R,\ i \ne j\}\ . \tag{1}$$

Here, dist (v_i, v_j) denotes the distance between node i and node$j$.

3.1.2. Coverage disk area. The sense coverage area of v is called the coverage disk area. If the coordinates of node v are x, y, the coverage disk area is a circle centered at x, y with radius r. It is defined as follows:

$$ca\,(v) = \{q|\mathrm{dist}(v, q) \le r\}\ , \tag{2}$$

where q is a point located in region A.

3.1.3. Coverage model. Can be defined using the Boolean disk model, i.e., any location $q(x_q, y_q)$ in the coverage disk area of sensor node $v(x_v, y_v)$ that is covered by v, others not.

3.1.4. Coverage rate. Divide region A into $a \times b$ grids. Coverage rate CR is the ratio of the number of covered grids to the number of all grids, defined as

$$CR = \frac{\sum_{i=1}^{a\times b} g_i}{a \times b}\,, \tag{3}$$

where $g_i = 1$ if grid i is covered by a node and $g_i = 0$ if grid i is not covered by any node.

3.1.5. Coverage efficiency. The coverage efficiency CE is the ratio of the union covered area by all sensor nodes in A and the sum of all nodes' coverage disk areas

$$CE = \bigcup_{v\in V} \frac{ca(v)}{\sum_{v\in V} ca(v)}\,. \tag{4}$$

The value of CE is an indicator of the redundancy of all nodes. The larger is CE, the higher is redundancy.

3.2. The node layout for full coverage

Obviously, single node's sensing area coincides with the coverage disk. However, the union sensing area of multiple nodes is determined by the layout of nodes.

There exist three layouts of two neighboring nodes' coverage disk area. It is just as shown in Fig. 1. The nodes v_2, v_3 and v_4 are neighbors of node v_1. The distance d_1 between node v_1 and v_2 is shorter than sense radius r. There is overlapping sensing coverage area between these two nodes. The distance d_2 from node v_1 to node v_3 is twice the sense radius r, i.e. communication radius R. Then two coverage disks are tangent each other. There is only one point on the mutual tangent and no overlapping coverage area. The distance d_3 from node v_4 to node v_1 is longer than r and shorter than R. It causes blind zone which is not covered by any node. Thus, the coverage capacity is related to the layout of nodes. If the number of nodes $n \le 2$ and there is no overlapping coverage area, the coverage is not affected by the nodes layout. If the node number $n \ge 3$, it could form coverage blind zone among the disjointed coverage disks (the shadow area in Fig. 2). It requires deploying more nodes in order that the blind zone is covered totally.

The blind zone can be eliminated by using multiple nodes' overlapping coverage. As shown as Fig. 3, upper part, three nodes' coverage disks intersect at a same point. The segments between any two nodes form an equilateral triangle. When the triangle sides length, i.e. the nodes' distance $d_0 = \sqrt{3}r$, the coverage efficiency of these three

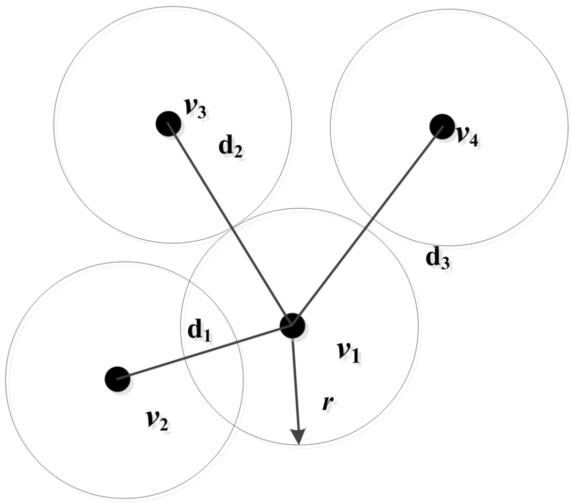

Fig. 1. Different layouts of two coverage disks

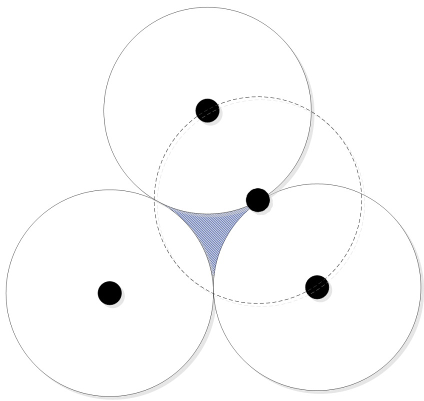

Fig. 2. Blind zone among disjointed coverage disks

nodes is the best. In this case, the overlapping area is calculated by formula

$$S_b = 6\left(\frac{1}{6}\pi r^2 - \frac{\sqrt{3}}{4}r^2\right) . \tag{5}$$

An optimal layout of sensor nodes offering full coverage can be obtained by a triangular lattice [16], as shown in Fig. 3, bottom part. In this case, the effective coverage area of a node is calculated by formula

$$S_n = \frac{3\sqrt{3}}{2}r^2 . \tag{6}$$

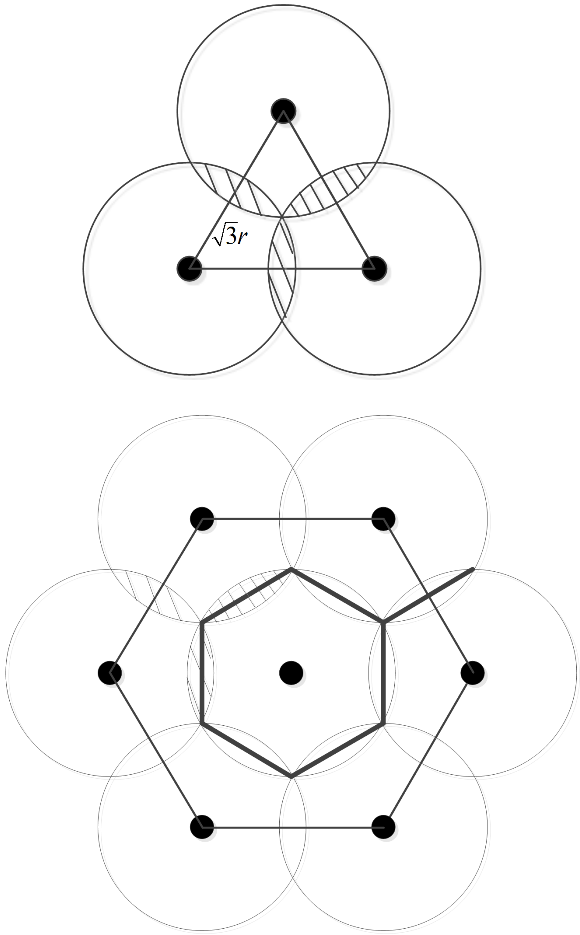

Fig. 3. Layout for full coverage: up–layout for full coverage of three nodes, bottom–triangular lattice layout

Let n denote the number of nodes using triangular lattice deployment which offers full coverage in region A of $L \times W$. Now n can be expressed as

$$n = \frac{2M \times N}{3\sqrt{3}r^2}\,. \tag{7}$$

However, due to the shape and side length factor, it is more likely that n nodes cannot cover the region of $L \times W$ fully. First of all, it is necessary to ensure that every point on the border is covered by a rectangle monitoring region. Therefore, nodes can be deployed as in Fig. 4 to cover border as few as possible. We can estimate the node number of full coverage on this condition. First, we have to determine the number w of nodes covering the side of length W in the horizontal dimension and then the number l of nodes in vertical dimension. We use the formulae

$$w = \left\lfloor \frac{W}{\sqrt{3}r} \right\rfloor \tag{8}$$

and

$$l = 2\left\lceil \frac{L}{3r} \right\rceil + \alpha\,, \tag{9}$$

where

$$\alpha = \begin{cases} 1 & \text{if } (L \bmod 3r) \le r\,, \\ 2 & \text{if } (L \bmod 3r) > r\,. \end{cases}$$

According to formula (8) and (9), the number of nodes offering full coverage in monitoring region A is given by the formula

$$N_{\text{fc}} = l \times w\,. \tag{10}$$

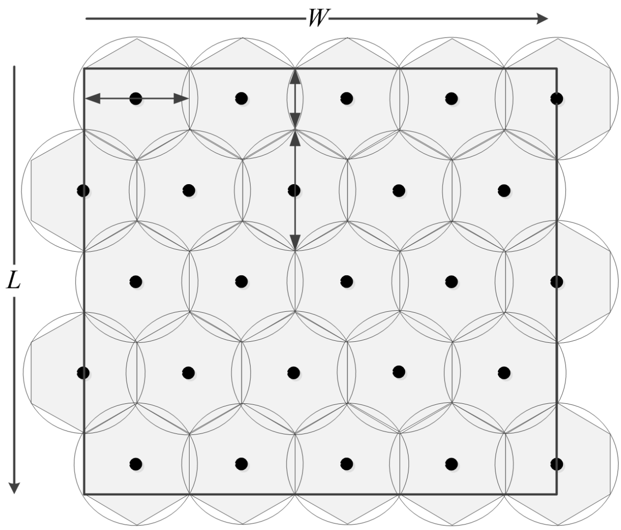

Fig. 4. Ideal node layout offering full coverage in a rectangular region

4. Computations

4.1. Judgment rule of self-adjusting

From the above discussion, we know that the ideal distance between two nodes to obtain the best coverage is $\sqrt{3}r$, denoted as d_0. Thus, the nodes can be adjusted as follows to close the triangular lattice layout based on the local location of neighbors.

Let v_i denote a scheduling node, v_j being a v_i's neighbor. If the distance between the two nodes is less than d_0, it means that there is too much coverage overlap between them. Thus, v_j will be moved opposite to v_i to reduce the coverage overlap area. Otherwise, if the distance is greater than the threshold d_0, v_j will move towards v_i to fully cover the gap between them. As shown in Fig. 1, node v_2 should move oppositely to v_1, on the contrary, v_4 should move toward v_1.

4.2. Node position updating

Assume that node v_j is a neighbor of node v_i. If $d(v_i, v_j) \neq d_0$, then let node v_j move by $d_\mathrm{m} = d_0 - d(v_j, v_i)$. When $d_\mathrm{m} < 0$, the movement of node v_j should be opposite to node v_i. When $d_\mathrm{m} > 0$, node v_j will move towards node v_i. The direction of movement depends on the angle θ from v_j to v_i. The value of θ can be calculated according to the position of the two nodes. The coordinate of node v_j is then updated in the following way:

$$\begin{cases} {x_j}' = x_j + \varepsilon \cdot d_\mathrm{m} \cdot \cos\theta \,, \\ {y_j}' = y_j + \varepsilon \cdot d_\mathrm{m} \cdot \sin\theta \,. \end{cases} \tag{11}$$

Here, ε represents the movement coefficient, that is given as

$$\varepsilon = 1 - \frac{7}{24} CR$$

in this paper.

4.3. LLSAD algorithm

From the above analysis, LLSAD algorithm we proposed is shown in Fig. 5. First of all, it initializes task region border parameter as $L \times W$, and determines the sensor node number n by the formulae (9) and (10). And then, randomly deploys the nodes in the task region (line 1). The operation of LLSAD is divided into rounds where each round is further divided into 4 steps as follows from Fig. 5.

1. Calculate the current coverage rate CR. If $CR > C0$ ($C0$ denoting the required coverage ratio), the algorithm will quit, otherwise it will perform step 2 (lines 3–6 in Fig. 5).

2. Traverse every node and exchange latest location information between every two nodes via broadcast (lines 7–8 in Fig. 5).

3. For each neighboring node v_j of node v_i, calculate their distance $d(v_j, v_i)$. According to the adjusting judgment rule determine, whether to update the nodes' location or not (lines 9–14 in Fig. 5).

4. After scheduling all the nodes (line 15), every node moves to the new location. And then it begins the new round and jump to Step 1.

```
Initialize the network in region A;
For each round
 Calculate the coverage rate CR;
 If (CR>CR_req)
  break;
 end if
 For each node v_i(i=1: n)
  Exchange location message with all neighbors in one-hop range;
  for each neighbor v_j(j=1:N(v_i))
   if (d(v_j,v_i)≠d_0)
    Calculate the azimuth angle θ that v_j relative to v_i;
    Calculate the movement and update location of v_j.
   end if
  move to next neighbor
 move to next node
 Each node moves to lastest location;
move next round;
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Fig. 5. Flowchart of LLSAD algorithm

5. Performance evaluations

The algorithm evaluation is simulated in the MATLAB R2013a. The evaluation metrics includes coverage rate CR and coverage efficiency CE as well as average running rounds to meet the coverage rate required CR_{req}. In order to evaluate the algorithm performance under different conditions, we tested LLSAD in two initial scenarios. One scenario is S_1 where all nodes are initially randomly deployed in the whole monitoring region, as shown in Fig. 6. In another scenario S_2, all nodes are split in half and initially randomly deployed in the two 1/4 diagonal area of task region, as shown in Fig. 7. Besides, we compared LLASD and VFP algorithms under the scenario S_1.

We set two task region sizes corresponding to each case in formulae (9) and (10), including $80\,\mathrm{m}\times 80\,\mathrm{m}$ and $100\,\mathrm{m}\times 80\,\mathrm{m}$. Thus, we can build many settings of different scenarios and sizes of region. The details of settings and CR requirements are shown as Table 1. The initial coverage rate of each random network in scenario S_1 is less than 80 %, and is not larger than 60 % in S_2.

Table 1. Simulation settings

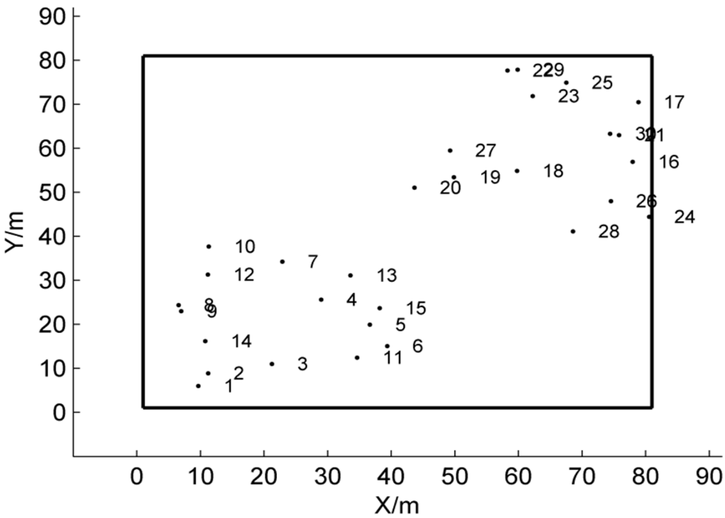

Fig. 6. Nodes are randomly deployed in the whole region

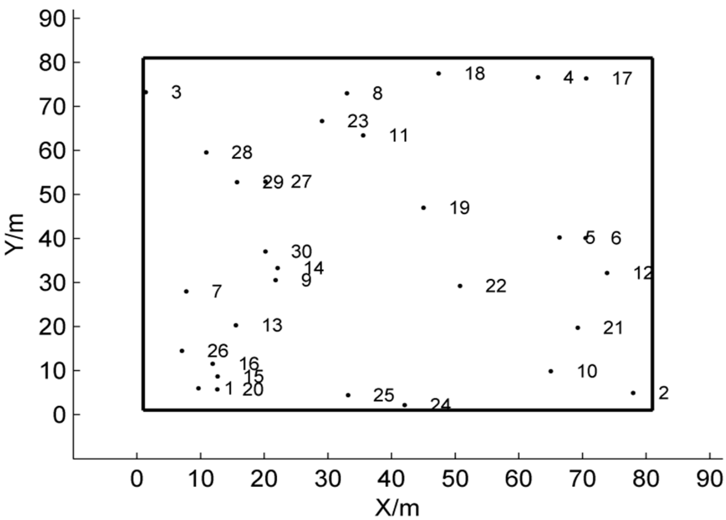

Fig. 7. Nodes are deployed on the two opposite angles

settings	scenario S_1 nodes/CR_{req}	scenario S_2 nodes/CR_{req}	region size $L \times W$	sensing radius r
1	28/94 %	28/93 %	80 m×80 m	10 m
2	29/95 %	29/94 %	80 m×80 m	10 m
3	30/95 %	30/95 %	80 m×80 m	10 m
4	30/95 %	36/95 %	100 m×80 m	10 m

Table 2. Results of simulation under scenario S_1

settings	nodes	CR_{req}	rounds	CR	CE	region size
1	28	>94 %	9.4348	0.9421	0.6854	80 m×80 m
2	29	>95 %	9.1986	0.9539	0.6701	80 m×80 m
3	30	>95 %	6.8482	0.9553	0.6487	80 m×80 m
4	36	>95 %	9.2758	0.9540	0.6749	100 m×80 m

Table 3. Results of simulation under scenario S_2

settings	nodes	CR_{req}	rounds	CR	CE	region size
1	28	>93 %	10.9627	0.9341	0.6797	80 m×80 m
2	29	>95 %	12.1865	0.9445	0.6635	80 m×80 m
3	30	>95 %	11.3478	0.9543	0.6481	80 m×80 m
4	36	>95 %	14.9953	0.9532	0.6743	100 m×80 m

According to the formula (8) and (9), it needs to deploy 30 nodes in 80 m×80 m and 36 nodes in 100 m×80 m region to obtain full coverage. Under every configuration, the algorithm operates 100 runs, respectively. The evaluation results are as shown in Table 2 and Table 3 under different settings of region size and initial deployment.

In all settings, the maximum of average iterating rounds to meet the coverage requirement is 14.9953, and the minimum is only 6.8482. This illustrates that LLSAD is able to improve the coverage by redeploying under these two scenarios.

Under scenario S_1, LLSAD improves network coverage rate rapidly when sensor nodes are placed randomly in whole monitoring region at initialization. In the region of 80 m×80 m deployed randomly 28 nodes (93.5 % of N_{fc}), LLSAD only runs for 9.4348 rounds in average when the CR increases to 94 %. If the number of nodes increases to N_{fc}, the average rounds are not more than 10 in the two regions. There are only 6.8482 rounds, 9.2785 rounds in the regions of 80 m×80 m, 100 m×80 m respectively. LLSAD provides an effective redeployment for improving coverage.

Under scenario S_2, LLSAD runs more rounds to achieve CR_{req} (see Table 3).It runs nearly 15 rounds in average in the worst case to obtain CR_{req}. This is because the nodes are only placed in half area at initialization so that the nodes are dense with a low coverage rate. The movement of one node affects the coverage of multiple neighbors. Hence, the nodes have to adjust over and over to form a uniform distribution with higher coverage rate. Even if the number of nodes is N_{fc}, the algorithm runs more rounds under scenario S_2. In the settings of line 3 and 4 in Table 4, there is 5 %–6 % of the simulations have run more than 40 rounds to reach CR_{req}. What is more, the algorithm achieves much better average coverage efficiency when the number of node is less than N_{fc}. The small number is, the higher CE is. It is just because the overlaps between the nodes are reduced by LLSAD to achieve the CR_{req}.

In a word, the LLSAD algorithm has the capacity to enhance coverage by self-adjusting based on the local locations of the nodes under two scenarios. And it will run fewer rounds to achieve the required coverage rate if the nodes are placed uniformly with a relative high coverage rate in initial deployment.

In addition, we compare LLSAD and virtual force (VF) position algorithm in term of convergence and coverage rate. We evaluate the two algorithms in $80\,\mathrm{m}\times 80\,\mathrm{m}$ region deployed 30 nodes under the scenario S_1. Both average results of 25 rounds calculated from 20 random initial deployment are shown in Fig. 8. The LLSAD algorithm only runs 5 rounds in average to reach the required coverage rate 95 % and keeps stable after 10 rounds. In contrast, VF's coverage rate increases slowly and only reaches 92 % after 25 rounds. LLSAD is a very fast and efficient deployment for MSN, which defeats VFP in terms of convergence and coverage capacity.

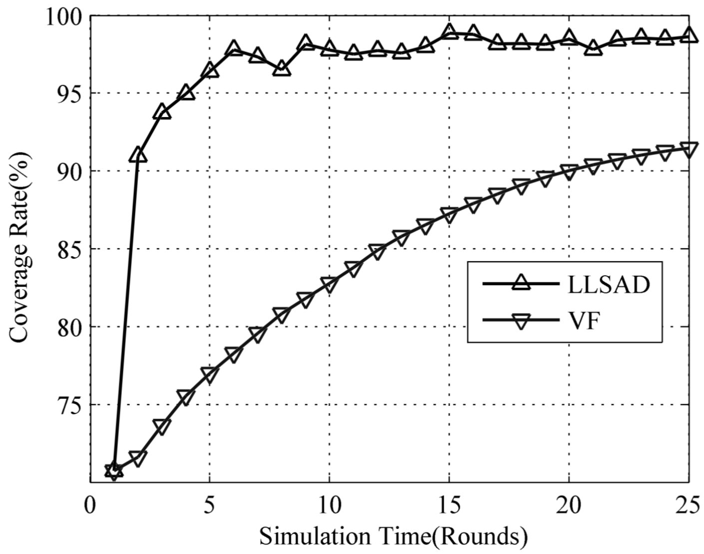

Fig. 8. Comparison of LLSAD and VF under scenario S1

6. Conclusion

The issue of deployment and coverage is fundamental in WSN, which is basic to data fusion, routing techniques as well as management in upper application. In this paper, we have proposed a new adaptive deployment algorithm for mobile sensor networks, namely, local location based self-adjusting deployment algorithm. By using only location information of local neighbors for the self-adjustment of each node, sensor nodes can move to close optimum location of the perfect coverage layout. The results of the simulations show that LLSAD is a fast, efficient redeployment for mobile sensor networks. Without getting and maintaining the global topology information of sensor nodes, each node runs the algorithm with low cost. Therefore, LLSAD is applicable to mobile sensor network with constrained resources.

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