

MOBILE NODE DEPLOYMENT IN HYBRID SENSOR NETWORKS

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Abstract—Hybrid sensor networks consisting of both static and mobile sensor nodes attract more research interests with their enhanced capability. As mobile nodes generally have more power than static nodes, they are preferable to be used as cluster heads. In this paper, we study the mobile node deployment problem with the objective of maximizing the number of static nodes covered by the mobile nodes with minimized moving distance. We prove that this problem is NP-complete and propose a distributed deployment protocol to solve it. In the proposed protocol, different policies of selecting the moving nodes are considered to cover more static nodes with less moving distance. Simulation results show that the proposed protocol achieves high coverage ratio with acceptable moving distance.

Index Terms—Wireless sensor networks, deployment, NP-complete, distributed protocol.

I. INTRODUCTION

In recent several years, there has been a growing interest to study and build hybrid sensor networks consisting of both static and mobile nodes [7], [9]. In [1], mobile base stations are used to increase the lifetime of wireless sensor networks. Many other work is focused on how to deploy mobile sensors in hybrid sensor networks. Several different approaches have been proposed to solve the problem, including the virtual force based algorithms [4], [13], the movement-assisted deployment protocols based on Voronoi diagrams [9], [11], and the incremental self-deployment algorithm [5]. Most of these work is focused on approaches to maximize the coverage of sensing area and minimize the movement cost (typically measured by the moving distance) [4], [7], [11], [13]. However, no work considers the impact of the deployment of mobile sensors to the network topology and consequently to the overall energy consumption of the sensor network.

The network topology is particularly important for large-scale sensor networks, which typically employs clustered architecture [3] or layered architecture [12]. In a clustered sensor network, the cluster head plays an important role for data forwarding and managing nodes belonging to its cluster. In our study, we propose to use mobile sensors to function as cluster heads in hybrid sensor networks. In this model, the major objective of deploying mobile nodes is to maximize the number of static sensors that can be covered by the mobile nodes. Due to the difference of network models, the deployment approaches targeting to maximize the geographical coverage [4], [11], [13] cannot be directly applied to solve this problem. Fig. 1 illustrates such an example with four mobile nodes. The deployment shown in Fig. 1(a) maximizes the geographical coverage but not the number of static nodes

covered by the mobile nodes, as the deployment shown in Fig. 1(b) does.

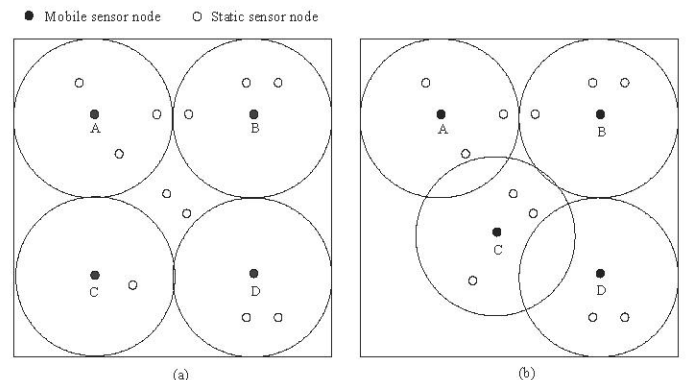


Fig. 1. Deployment of mobile sensor nodes.

In this paper, we will study the mobile node deployment problem with the objective of maximizing the number of static nodes covered by mobile nodes with minimized moving distance. We first show this problem is NP-complete and then propose a distributed deployment protocol with various policies of selecting the mobile nodes to be moved. The rest of the paper is organized as follows. Section II gives the problem description and proves its NP-completeness. In Section III, the distributed deployment protocol is proposed. Section IV presents the simulation results of the proposed protocol. Section V concludes the paper.

II. THE MDP-SC PROBLEM

In hybrid sensor networks consisting of both static and mobile nodes, mobile nodes generally have more power than static nodes [8], which makes them preferable to be used as forwarding nodes. Hence, in this work, we assume that static nodes are mainly used to sense and collect data, while mobile nodes are mainly used to forward data. When there are not enough mobile nodes in the network, static nodes can also be used as forwarding nodes. Each static/mobile node has its fixed transmission range, and the transmission range of a mobile node is larger than that of a static node. For simplicity, we assume that each mobile node can reach the base station in one-hop. Also it is assumed that each sensor node has a unique pre-configured id and can get its location information by GPS.

Initially, the static and mobile nodes are deployed randomly. Some static nodes may be unable to communicate with any mobile node. In order to guarantee that the data information sensed by the static nodes can be transmitted to the base station, each static node should be covered by at least one

mobile node if possible. The problem studied in this paper is to maximize the static nodes covered by the mobile nodes in a hybrid sensor network with minimized moving distance. We refer this problem as the Mobile node Deployment Problem for maximizing Sensor Coverage (MDP-SC). We first show that the MDP-SC problem is NP-complete.

Theorem 1: The decision version of the MDP-SC problem is NP-complete.

The theorem can be proved by reducing from the Minimum Weight Set Cover problem [2], a well-known NP-complete problem. Due to space limit, the proof is omitted here.

III. DISTRIBUTED DEPLOYMENT PROTOCOL

In this section, we propose a distributed deployment protocol to solve the MDP-SC problem. To maximize the number of covered static nodes, intuitively, mobile nodes should move to a new location where more additional covered static nodes can be obtained. When a mobile node leaves its original location to cover some uncovered static nodes, it may result in some static nodes covered at its original location to be uncovered. We define the *gain* of a movement as the difference of the number of static nodes to be covered and the number of static nodes to be uncovered caused by the movement. Thus, a mobile node moves to a new location only if the movement gain is greater than 0. We refer such a movement as a *valid movement*. In the case that there is no mobile neighbor that can make a valid movement, the mobile neighbors can forward the request to its one-hop mobile neighbor.

To find the *target location* which yields the maximum movement gain with the minimum moving distance, the static nodes are used to detect the uncovered static nodes among their static neighbors, estimate the number of uncovered static nodes, and send movement requests to their mobile neighbors. For simplicity, the target location can be set as the location of the requesting static node. If there exists such a mobile neighbor which can make a valid movement, the two-hop cascaded movement [10] is employed to reduce the total moving distance.

In the following, before we present the distributed deployment protocol, we first provide the notations and definitions of packets used in the distributed protocol.

Notations:

$S_{uncovered_neighbor_num}(S_k)$: the number of uncovered static neighbors of the static node S_k ;
 $S_{additional_uncovered_num}(M_i, S_k)$: the number of additional uncovered static neighbors after the mobile node M_i leaves the original location to cover the uncovered static neighbors of S_k ;
 $S_{additional_replace_uncovered_num}(M_j, M_i)$: the number of additional uncovered static neighbors generated by the movement of M_j to replace M_i ;
 $distance(M_i, S_k)$: the distance between mobile node M_i and static node S_k ;
 $sub(M_i)$: the mobile node that will replace the mobile node M_i when it leaves its original location;
 $replace_distance(sub(M_i), M_i)$: the moving distance of $sub(M_i)$ to replace M_i ;
 $total_replace_distance(M_j, M_i, S_k)$: the total replacement moving distance which is the sum of $replace_distance(M_j, M_i)$ and $distance(M_i, S_k)$.

Here we assume each mobile node maintains the information (id and location) of its mobile neighbors in the *mobile-neighbors* structure and its static neighbors in the

static-neighbors structure, respectively. The information of the requesting static nodes is stored in the *request-reporters* structure. Similarly, each static node maintains its *mobile-neighbors* and *static-neighbors* structures.

Fig. 2 shows the distributed deployment protocol which operates in three phases: *Initialization*, *Deployment Negotiation*, and *Movement and Information Update*. There may be multiple rounds of the II and III phases until no mobile node moves. In the following, we will describe each phase in details.

Packets:

MIP: the Mobile node Information Packet, which consists of id and location information of a mobile node;
SIP: the Static node Information Packet, which consists of id, location, and the mobile neighbors of a static node;
DRP: the Deployment Request Packet, which consists of id and the number of uncovered static neighbors of a static node;
DRSP: the Deployment Response Packet, which consists of id, moving distance (or total replacement moving distance), and the movement gain of a mobile node;
RRP: the Replacing Request Packet, which consists of id, the number $S_{uncovered_neighbor_num}(S_k)$, and the information of additional uncovered static nodes of a mobile node;
RRSP: the Replacing Response Packet, which consists of id, target mobile node id, the target location, the movement gain, and the replacement moving distance of a mobile node;
DDP: the Deployment Decision Packet, which consists of id and target mobile node id;
RDP: the Replacing Deployment Packet, which consists of id and target mobile node id;
BMP: the Before Movement Packet, which consists of id and target location of a mobile node;
AMP: the After Movement Packet, which consists of id and location of a mobile node;
SUP: the Static node Update Packet, which consists of id and location of a static node.

A. Phase I: Initialization

In the initialization phase, each mobile node will broadcast an MIP which encloses its id and location information. Each static node will then broadcast an SIP. After receiving the SIPs from its static neighbors, each mobile node gets the information of the static nodes covered by it and each static node gets the information of its uncovered static neighbors.

B. Phase II: Deployment Negotiation

The deployment negotiation phase consists of two steps.

In *Step 1*, the static nodes which have uncovered static neighbors will broadcast DRPs to their mobile neighbors. For each mobile node M_i , after receiving the DRP from a static node S_k , M_i will compute the movement gain $n'(M_i, S_k) = S_{uncovered_neighbor_num}(S_k) - S_{additional_uncovered_num}(M_i, S_k)$.

In *Step 2*, two cases are considered: 1) $n'(M_i, S_k) > 0$, and 2) $n'(M_i, S_k) \leq 0$. For the first case, it is worthy for M_i to move to S_k 's location. Then M_i will select one static node S_k to which the mobile node has the maximum $n'(M_i, S_k)$ and minimum $distance(M_i, S_k)$ and send a DRSP to S_k . After receiving the DRSPs from its mobile neighbors, the static node S_k then selects one mobile node M_i which has the maximum $n'(M_i, S_k)$ and minimum $distance(M_i, S_k)$.

For the second case, it is unnecessary for the mobile node M_i to move because the movement can not bring movement gain. For this situation, we employ a two-hop cascaded movement scheme, in which the mobile node which cannot make

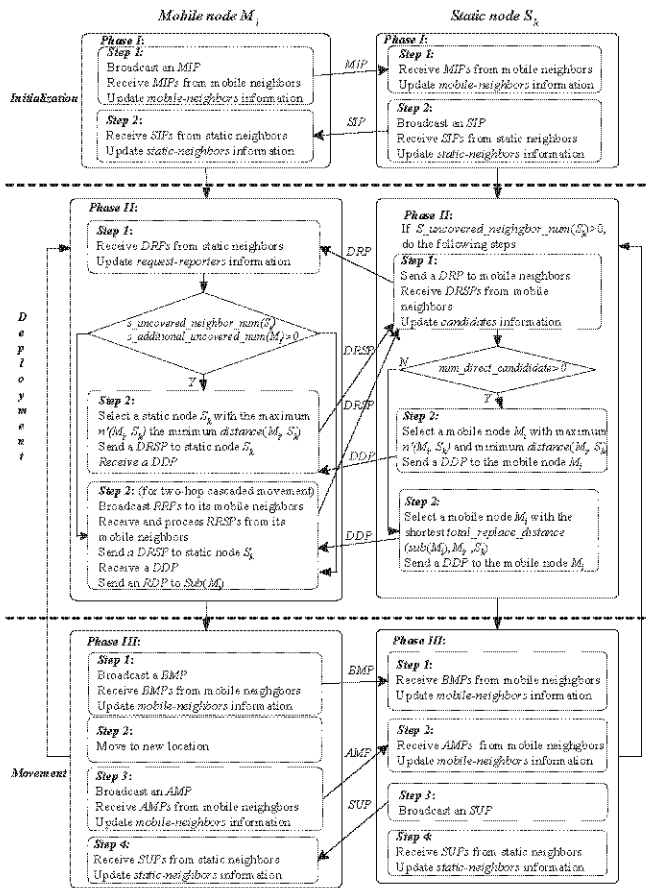


Fig. 2. Distributed deployment protocol.

an invalid movement (referred as the *replaced mobile node*) moves to the target location and one of its one-hop mobile neighbors, referred as the *replacing mobile node*, moves to replace it. One problem arising in the two-hop cascaded movement scheme is: How to decide the new location of the replacing mobile node? The criteria used here is to minimize the moving distance while covering all the uncovered static nodes caused by the movement of the replaced mobile node. In the following, a three-step approach (as shown in Fig. 3) is proposed for guiding the two-hop cascaded movement process.

In *Step i*), the mobile node which cannot make a valid movement broadcasts an RRP to its one-hop mobile neighbors. After receiving an RRP from a mobile node M_i , a mobile neighbor M_j will compute the replacing target location, $replace_distance(M_j, M_i)$, then get $total_replace_distance(M_j, M_i, S_k)$, and $S_additional_replace_uncovered_num(M_j, M_i)$. Then, the M_j will calculate the overall movement gain $n''(M_j, M_i) = S_uncovered_neighbor_num(S_k) - S_additional_replace_uncovered_num(M_j, M_i)$.

In *Step ii*), the mobile node M_j checks if $n''(M_j, M_i) > 0$, then M_j will send an RRSP packet to the requesting mobile node. The requesting mobile node M_i may receive more than one RRSPs, then it will select one mobile node M_j with the maximum $n''(M_j, M_i)$ and minimum $total_replace_distance(M_j, M_i, S_k)$ and set $sub(M_i) = M_j$.

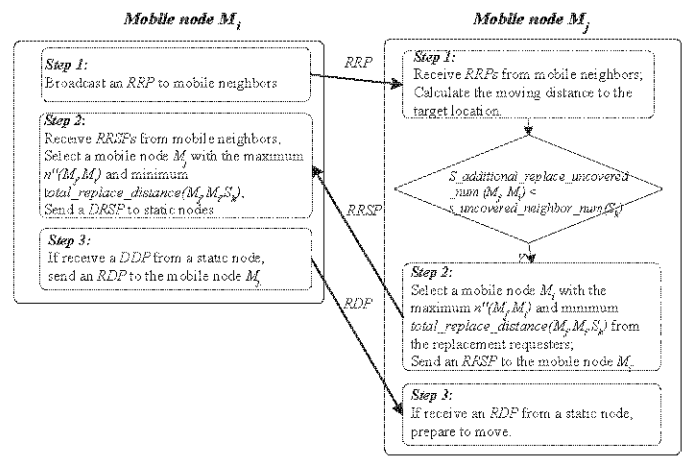


Fig. 3. Protocol used in the two-hop cascade movement process.

In *Step iii*), M_i will send the an RRSP to the initial requesting static node and wait for the final decision. As shown in Fig. 2, the static node S_k which receives one or more RRSPs will select the mobile node M_i which has the maximum $n''(M_j, M_i)$ and minimum $total_replace_distance(sub(M_i), M_i, S_k)$ and sends a DDP to M_i . If a mobile node M_i receives a DDP, which means it is selected to do the two-hop cascaded movement, it will send an RDP to the selected replacing mobile node $sub(M_i)$ before it enters Phase III.

C. Phase III: Movement and Information Update

The major task in Phase III is updating the neighbor information and finishing the movement. Before moving, each mobile node that will move broadcasts a BMP, and its neighbor static/mobile nodes will update the information of the sending mobile node. Then the mobile nodes will perform the actual movement. After a mobile node moves to the target location, it will broadcast an AMP to inform other nodes to update information. Then each static node who has its neighbor(s) changed will broadcast an SUP.

After Phase III, the deployment process returns to Phase II and starts a new deployment round until no more movement is made in Phase III.

D. Selection Policies

As described in Phase II of the protocol, a mobile node may be selected for movement due to one of the following situations (cases): 1) more static nodes will be covered with no additional uncovered static node (i.e., $n' > 0$ and $n_a = 0$, where n_a denotes $S_additional_uncovered_num$), 2) more static nodes will be covered with additional uncovered static node(s) (i.e., $n' > 0$ and $n_a > 0$), 3) the replacing mobile node has more static nodes covered than additional uncovered static nodes (i.e., $n'' > 0$). We observe that the selection criteria of the mobile nodes for movement and the selection order of the above three situations have a big impact to the total number of covered static nodes and the total moving distance. We consider six different selection policies (listed in Tab. I) that can be applied by the mobile nodes and static nodes in Phase II

Selection Policies	Selection Order	1st Priority Selection Criteria
1-tier by distance	all cases	the mobile node with the minimum moving distance
1-tier by number	all cases	the mobile node with the maximum movement gain
2-tier by distance	tier 1: cases 1&2 tier 2: case 3	the mobile node with the minimum moving distance the mobile node with the minimum total replacement moving distance
2-tier by number	tier 1: cases 1&2 tier 2: case 3	the mobile node with the maximum n' the mobile node with the maximum n''
3-tier by distance	tier 1: case 1 tier 2: cases 2 tier 3: case 3	the mobile node with $n_a = 0$ and minimum moving distance the mobile node with the minimum moving distance the mobile node with the minimum total replacement moving distance
3-tier by number	tier 1: cases 1 tier 2: cases 2 tier 3: case 3	the mobile node with $n_a = 0$ and maximum n' the mobile node with the maximum n' the mobile node with the maximum n''

TABLE I
SIX SELECTION POLICIES IN THE PROPOSED PROTOCOL.

of the proposed protocol. The two selection criteria considered are “by number” (i.e., the maximum movement gain) and “by distance” (i.e., the minimum moving distance). Each policy has a prioritized selection criteria. The 2nd criteria will be used to break ties of selections based on the 1st criteria.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed deployment protocol, simulations have been conducted using the wireless sensor module developed on OPNET [6]. The sensor filed size is set as $100m \times 100m$. The six selection policies of mobile nodes are compared under three simulation settings: various number of static nodes (100 ~ 200), various number mobile nodes (3 ~ 11), and various transmission ranges of the static nodes ($10m \sim 60m$). The transmission range of mobile nodes is set as $100m$. Four performance metrics are considered: the coverage ratio (number of covered static nodes/number of static nodes), the average moving distance (total moving distance/number of mobile nodes), the average number of movements (total number of movements/number of mobile nodes), and the number of rounds to stop. Due to space limit, the last two metrics are not shown. In all simulations, the static nodes and the mobile nodes are initially deployed randomly.

Figs. 4-5 show the first two performance metrics under various number of static nodes when there are 5 mobile nodes and the transmission range of the static nodes is set as $30m$. As shown in Fig. 4, all six selection policies achieve the best coverage ratio for 100 static nodes and their coverage ratios all decrease with more number of static nodes. This is consistent with our intuition. Compared with 1-tier policies, the corresponding 2-tier policies generally achieve better coverage ratio as non-replacement situations are considered first which may help cover more static nodes. For similar reason, the

corresponding 3-tier policies achieve the best coverage ratio in most cases. As shown in Fig. 5, in general, the average moving distances for all six selection policies have slight changes with more static nodes. The 2-tier policies generally have the least average moving distance compared with their corresponding 1-tier and 3-tier policies.

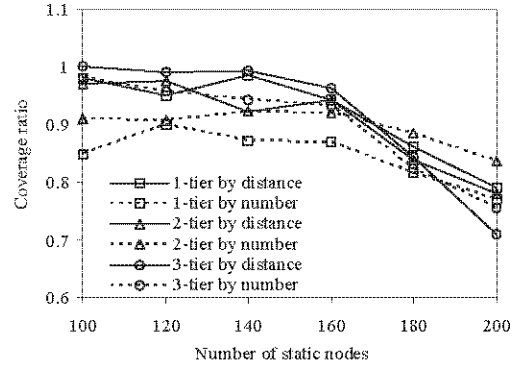


Fig. 4. Coverage ratio vs. number of static nodes.

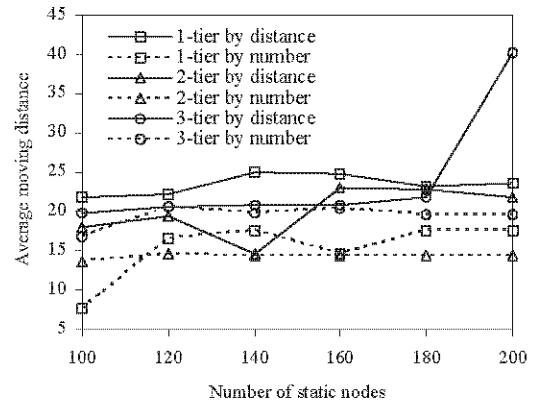


Fig. 5. Average moving distance vs. number of static nodes.

Figs. 6-7 show the first two performance metrics under various number of mobile nodes when there are 160 static nodes and the transmission range of the static nodes is set as $30m$. From Fig. 6, we see that all six selection policies achieve better coverage ratios with more number of mobile nodes. Fig. 7 shows that the average moving distances for most selection policies are increasing from 3 mobile nodes to 5 mobile nodes and decreasing with more than 5 mobile nodes. The reason is that with 5 mobile nodes, better selections can be made than with 3 mobile nodes, which result in significant improvement in coverage ratios at the cost of more average moving distances. When more mobile nodes are available, the initial coverage tends to be larger. Hence, the moving conditions are less satisfied, which result in slight improvement in coverage ratios with less average moving distances.

Figs. 8-9 show the first two performance metrics under different transmission ranges of static nodes when there are 5 mobile nodes and 160 static nodes. From Fig. 8, we see that all six selection policies achieve better coverage ratios when transmission range changes from $10m$ to $30m$ and from $40m$ to $60m$. Fig. 9 shows that the average moving distances for all

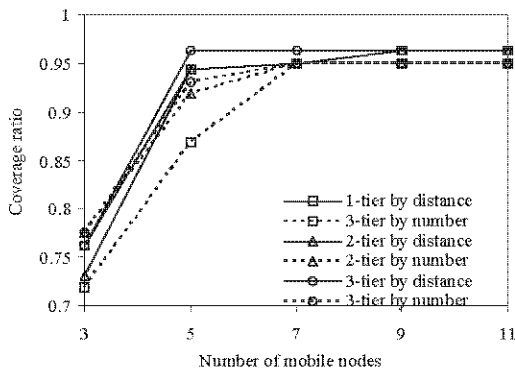


Fig. 6. Coverage ratio vs. number of mobile nodes.

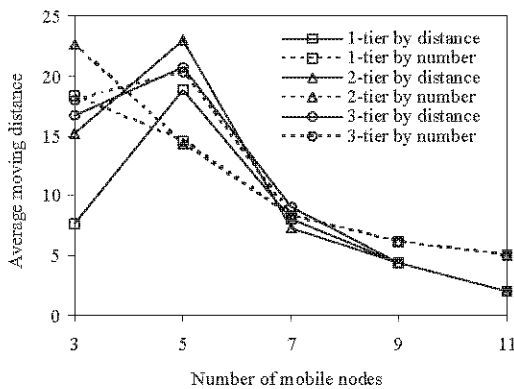


Fig. 7. Average moving distance vs. number of mobile nodes.

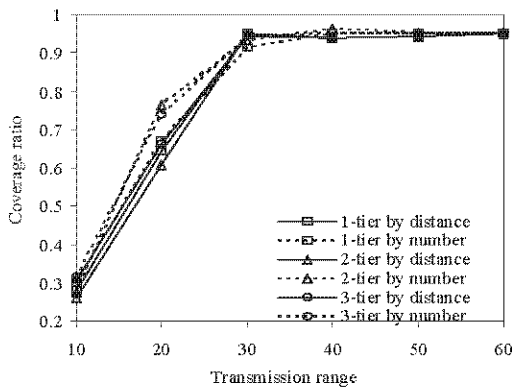


Fig. 8. Coverage ratio vs. different transmission range of static nodes.

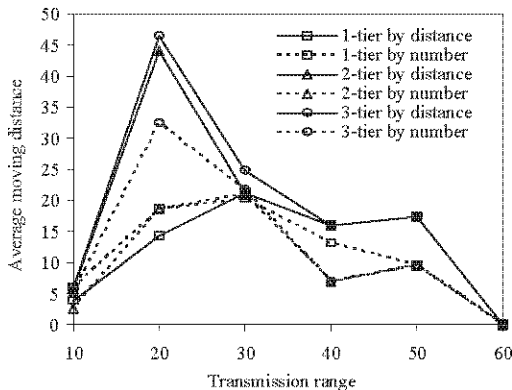


Fig. 9. Average moving distance vs. different transmission range of static nodes.

six selection policies are increasing when transmission range is lower than $20m$ (or $30m$) and generally decreasing with transmission range higher than $20m$ (or $30m$). The reason is that when the transmission range is changed from $10m$ to $20m$ (and up to $30m$), a static node can reach more mobile nodes, which will make it possible to make more selections. This is reflected in significant improvement in coverage ratios at the cost of more average moving distances. When the transmission range keeps increasing, the initial coverage ratio tends to be larger. Hence, the moving conditions are less satisfied, which result in slight improvement in coverage ratios with less average moving distances.

V. CONCLUSION AND FUTURE WORK

In this paper, we investigated the mobile node deployment problem in hybrid mobile sensor networks with the objective of maximizing the number of static nodes covered by mobile nodes with minimized moving distance. We proved that this problem is NP-complete and proposed a distributed deployment protocol to solve this problem. Different selection policies were considered in the proposed protocol to cover more static nodes with less moving distance. Through simulations, we showed that the proposed protocol achieves high coverage ratio with acceptable moving distance.

As one may notice that, the packets transmitted in the deployment process consume energy at both static and mobile nodes. Our next step is to improve the deployment protocol by reducing the number of packets transmitted. Another future work is to study how to balance the load of mobile nodes and construct energy-efficient cluster structure.

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