A Hybrid Solution For Coverage Enhancement In Directional Sensor Networks

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***Abstract*—In directional sensor networks (DSNs), motility capability of a directional sensor node has a considerable impact on the coverage enhancement. Motility capability may overcome overlapped field of views and occluded regions occurring during the initial deployment. On the other hand, adjusting working directions could not always heal coverage holes. Using mobility is the only solution under these circumstances. However, the high cost of mobile sensors and the high energy consumption of their physical movement are the two important constraints for their use. In this study, a hybrid solution has been proposed for the coverage improvement in DSNs. This hybrid solution increases the total coverage by up to 31% after the initial deployment. Besides, a new hybrid deployment model for DSNs has been discussed and the performance results of this model have been presented.**

***Keywords*-Directional Sensor Networks; Coverage; Cost; Energy Efficiency; Motility; Mobility; Hybrid Deployment**

I. Introduction

The coverage problem in omni-directional sensor networks has been intensively studied in the past decade [1]. There are two main methods for coverage improvement in omni-directional sensor networks. *redeployment/movement of sensor nodes*. On the other hand, coverage problems in directional sensor networks require more specific solutions since directional sensor nodes equipped with ultrasound, infrared and video sensors may work in several directions. Exploiting motility capability of those nodes is one of the basic solutions.

In a randomly deployed DSN, there might be overlapped areas and occluded regions after the initial deployment. A directional sensor node with motility capability could adjust its working direction along x, y, and/or z axes. Thus, the node provides itself with a new field of view (FoV) without moving to a different location. This new direction possibly contributes to a better total coverage by *(i) minimizing overlapped areas* and *(ii) providing occlusion-free FoVs*. Available solutions to the coverage problem exploit motility rather than mobility due to its nominal cost and low energy consumption [2]. Since a directional sensor node maintains its geographical position while adjusting its FoV, the node does not require an additional driving mechanism and/or GPS device. This effectively decreases the total production cost of the sensor node. Nevertheless, mobility may heal coverage holes where motility is inadequate/insufficient. However, mobility should be applied in a controlled manner because of its high energy consumption and the limited battery capacities of the sensor nodes.

To the best of our knowledge, existing solutions to the coverage problem in DSNs exploit either motility or mobility. In this paper, our main contribution is a distributed hybrid solution encouraging the use of both motility and mobility in a cascaded manner to improve the total coverage with minimum energy consumption. We discuss the idea of deploying hybrid directional sensor networks. Simulation results show that an optimum point for the deployment cost and the coverage improvement ratio could be achieved using a certain number of stationary, motile, and mobile nodes.

In Section II, existing solutions to the coverage problem in DSNs are discussed. Section III presents the directional sensing model and gives the details of the proposed hybrid solution. In Section III-B the idea of deploying hybrid sensor networks is addressed with respect to the coverage improvement and the cost of the network. Section IV presents the simulation results.

II. RELATED WORK

Existing solutions to the coverage problem in DSNs are categorized into four groups [3]. We will only discuss the studies aiming at maximizing the whole coverage, as we focus on the improvement of area coverage. Enhancing area coverage is very important for DSNs to fulfill the specified sensing tasks. A small unmonitored sub-area defeats the whole purpose of the network. However, random deployment may cause several problems, such as overlapped and occluded regions, uncovered areas, and broken sensor nodes. Therefore, three solutions have been proposed by the research community to overcome these difficulties. First solution is to redeploy new sensors after the initial deployment. Second solution is to adjust the working directions of the directional sensor nodes to improve the field coverage [4] [5] [6] [7] [8] [9]. The last one is to relocate the sensor nodes with mobility capability [10].

The study [4] is one of the pioneer works on coverage enhancement. The authors present a new method based on a rotatable sensing model. To achieve less overlapping area, a directional node repositions itself on the reverse direction of the interior angle-bisector occuring between two neighboring

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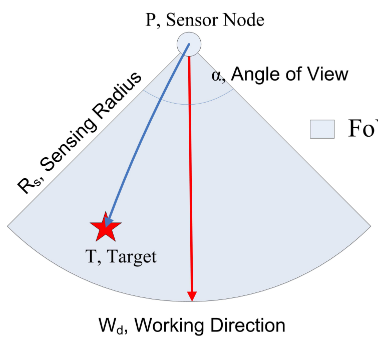

Figure 1. Directional Sensing Model

directional nodes. On the other hand, Cheng et al. describe the area-coverage enhancement problem as the Maximum Directional Area Coverage (MDAC) problem and prove the MDAC to be NP-complete [8]. The distributed solution for the MDAC problem, DGreedy algorithm, chooses the least overlapped direction as the new working direction. The authors observe that scarce sensors are highly critical to achieve maximal coverage, thus they utilize the number of sensing neighbors to differentiate node priorities.

Zhao and Zeng [5] propose an electrostatic field-based coverage-enhancing algorithm based on the Coulomb's Law to enhance the area coverage of wireless multimedia sensor networks by turning sensors to the correct orientation and decreasing the coverage overlaps of active sensors. They also aim at maximizing the network lifetime by shutting off as much redundant sensors as possible.

In [7], the authors name the above mentioned coverage problem as the optimal coverage problem in directional sensor networks (OCDSN). They propose a greedy approximation algorithm to the solution of the OCDSN problem, based on the boundary Voronoi diagram. By constructing the Voronoi diagram of a directional sensor network one could find the maximal breach path of this network. An assistant sensor traveling the edges of the Voronoi diagram determines which sensor to wake up in order to ensure the uncovered boundaries to be covered.

III. A Hybrid Solution To The Coverage Problem in DSNs

In this section, before presenting our hybrid solution, we will briefly explain the directional sensing model and the idea of hybrid deployment.

A. Directional Sensing Model

According to the binary detection model, a directional sensor node covers each point in its FoV. The common directional sensing capability for 2D spaces is illustrated in Figure 1. The sector covered by a directional sensor node S is denoted by a 4-tuple $(P, R_s, \overrightarrow{W_d}, \alpha)$, where P is the location, R_s is the sensing radius, $\overrightarrow{W_d}$ is the working direction, and α is the angle of view of the sensor node S.

Under ideal conditions without occlusion, a sensor node S covers an area with a size of $\frac{\alpha}{2}{R_s}^2$ units. The special case of this model, where $\alpha = 2\pi$ can be described as the omni-sensing model. For omni-directional sensors, there is only one possible working direction, whereas directional sensors have several possible working directions. However, they can work only at one direction at any given time t.

According to the binary detection model, a target point is covered when this point is located within a FoV of any directional sensor node. To find out as if this point is covered or not, the Target In Sector (TIS) test [11] needs to be applied to the related point. For area coverage problems, researchers opt for grid-based approach [12] to adapt this test model for indicating the (un)covered points in the observed area. Each point around the sensor node S is tested with the TIS test. The coverage map of the sensor node S is then created according to the test results.

B. Hybrid Deployment

We state that where the FoVs of two sensor nodes are overlapped, resolving overlapped region is still possible even only one of them has motility capability. Following this idea, we will elaborate on the effects of hybrid deployment in DSNs. There are three types of directional sensor nodes in DSNs. *stationary nodes, motile nodes,* and *mobile nodes*. Researchers have proved that motility and mobility significantly improve the total coverage in DSNs [3]. Nevertheless, networks consisting of motile/mobile directional sensor nodes require high budgets due to their considerable production cost. As an example, in [2], the cost of a stationary video camera, a pan-tilt-zoom video camera, and a mobile node are given as \$800, \$1300, and \$35000 respectively. The gap between the costs have definitely decreased and will continue to decrease in the future. However, there will always be a reasonable cost ratio between stationary, motile and mobile nodes. Thus, there is a necessity of hybrid directional sensor networks, where coverage improvement ratio and the cost of the network could be balanced. For example, the cost of a network built with mobile nodes is extremely high, whereas coverage improvement is impossible in DSNs consisting of only stationary nodes. Thus, we can assume that an optimum point for the cost and coverage improvement ratio could be achieved using a certain number of stationary, motile, and mobile nodes.

C. Cascaded Coverage Enhancement in DSNs

In randomly deployed directional sensor networks, the FoVs of two or more sensors might overlap and/or the FoVs of some sensors could be obscured by obstacles. In addition to these two problems, the working directions of some sensor nodes could be faced towards outside of the observed area.

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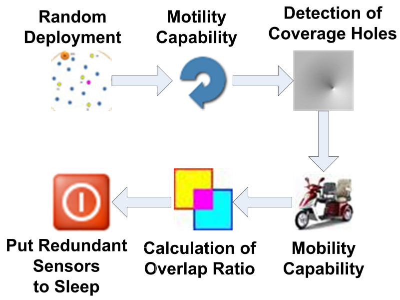

Figure 2. A block diagram of the proposed solution to the coverage problem in DSNs

As a consequence, the total coverage needs to be improved after the initial deployment. Most researchers exploit motility capability of directional sensor nodes for this purpose. To the best of our knowledge, only one study [10] proposes the use of mobility. However, in this study the authors do not exploit motility capability. Both approaches have pros and cons. For example, it is impossible to heal some coverage holes with motile sensor nodes, where coverage holes are far enough from any sensor node. The only way (except redeployment) to resolve these holes is to benefit from the mobility capability of the nodes. Nevertheless, mobility is highly expensive because of the associated high production cost and high energy consumption. Therefore, after the initial deployment, we first exploit motility to minimize the overlapped areas and occluded regions. Then, we check for possible coverage holes. If there are redundant sensor nodes and coverage holes, we redirect these nodes to the holes. A block diagram of this hybrid solution is given in Figure 2.

The key idea of this hybrid solution is to utilize both the motility and mobility in a cascaded manner. For exploiting the motility, we have proposed the AFUP algorithm to adjust the working directions of the directional sensor nodes after the initial deployment. AFUP is a heuristic distributed algorithm which uses the repel forces of uncovered points around the nodes. Directional sensor nodes exchange their location (P) and $\overrightarrow{W_d}$ information with neighboring nodes. Then, each node marks the covered points in its map. Afterwards, using neighboring nodes' information, the nodes determine the overlapped regions in their map. If the number of overlapped points are more than a predefined threshold, the node sets its working direction as the center (C) of the uncovered points in its map. Thus, the vector $\vec{PC}$ gives the new working direction of the node. The aforementioned steps are repeated until each node reaches its equilibrium state. In some regions, where the node density is high, some nodes could not find an appropriate working direction. To account for such conditions, these nodes update their status as balanced. For exploiting mobility, we have designed a new Window-based Neighborhood Exploring (WNE) algorithm whose details will be discussed in a future work.

Table I
AFUP ALGORITHM VS. RANDOM ALGORITHM

$R_s = 30m$, $\alpha = 60\,^{\circ}$, $Area = 250x250m^2$			
Number of Sensor Nodes	Random Deployment(%)	AFUP(%)	Coverage Gain (%)
$N = 25$	15.65	18.48	18.08
$N = 50$	28.28	34.95	23.59
$N = 75$	39.69	49.28	24.16
$N = 100$	48.38	60.56	25.18
$N = 125$	56.28	69.80	24.02
$N = 150$	63.26	77.23	22.08

IV. PERFORMANCE EVALUATION

We have implemented a simulation environment using MATLAB 7.8. Several test scenarios have been run in this environment to show *(i) the results of the AFUP algorithm, (ii) to find the node density where mobility is inevitable,* and *(iii) to analyze the relation between the cost of the network and the coverage improvement ratio in hybrid directional sensor networks*. We consider the total coverage and the overlap ratio as the two key metrics. The values for node density, sensing radius, and angle of view have been chosen with regard to the studies [13] and [5]. Accordingly, sensor nodes have been configured with an $\alpha = 60\,^{\circ}$ and a $R_s = 30m$. Simulations have been performed for random deployment in a rectangular two-dimensional terrain of $250x250m^2$. 15 different uniform random distributions have been generated for each individual scenario.

Simulation results show that motility significantly improves the total coverage after the initial deployment. Using only the local information of neighboring nodes, both overlapped areas are minimized and nodes near border are faced towards the observed area. Analyzing Table I shows that coverage gain varies from 18% to 25%. Especially, the coverage gain in dense networks is greater than in sparse networks. However, coverage gain starts to drop down when the network is saturated with sensor nodes.

Figure 3 shows the ratios of overlap minimization and coverage gain for different number of sensor nodes. Overlap minimization ratio shows by how much ratio the overlapped points are decreased after the initial deployment, whereas coverage gain indicates the rational increase of the total coverage after applying AFUP. As there are too many uncovered points in DSNs with low node density, directional sensor nodes could easily find appropriate working directions. Therefore, the overlap minimization ratio is considerably high in those networks. With increasing node density, the overlap minimization ratio starts to decrease. Facing the border nodes towards the observed area with increasing node density prevents the decrease of the overlapped areas. Thus, the overlapped areas might slightly increase above a certain threshold. This fact reveals that the use of mobility is inevitable for directional sensor networks with high node densities. Another course of action would be to put the redundant nodes into sleep in the absence of mobile nodes.

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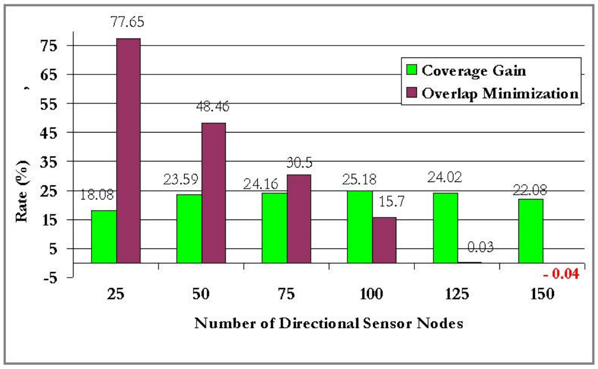

Figure 3. The relationship between the coverage gain ratio, the overlap minimization ratio and the number of sensor nodes

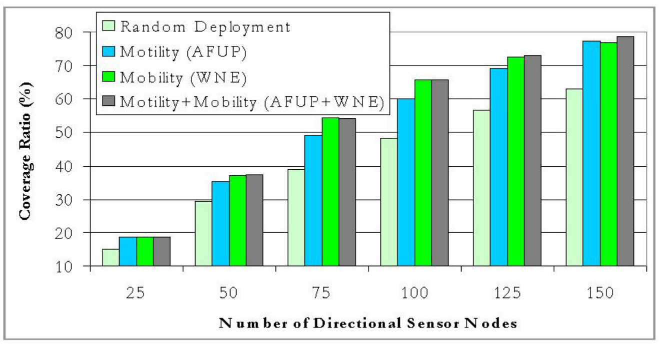

Figure 4. Coverage ratios of random deployment, AFUP, WNE, and AFUP+WNE

To explore the effect of mobility, we have utilized our WNE algorithm in the previously given scenarios. The preliminary results show that exploiting mobility after motility could increase the total coverage up to 6%. In the scenarios directional sensor nodes were assumed to exchange their location information only with nodes within their communication radius ($R_c = 2R_S$). Thus, this resulted in exploring coverage holes only within three sensing radii and therefore, mobility has a limited impact on the coverage gain. Exchanging information with nodes located within two-hop communication distance would definitely improve the coverage gain.

Solving the coverage problem only with mobility is expensive, whereas motility is inadequate to cope with coverage holes. Our experimental results, given in Figure 4, show that motility+mobility in DSNs provides a substantial coverage improvement. Furthermore, according to Table II and Figure 5 motility+mobility is also highly energy efficient compared to a mobility only solution. A mobility alone needs 2 to 9 times more sensors to change their physical location to achieve same coverage gain as in a motility+mobility solution. Moreover, the total travel distance in motile/mobile DSNs is substantially less than the total travel distance in mobile DSNs, as shown in Fig. 5

Table II
NUMBER OF MOVED DIRECTIONAL SENSOR NODES. MOBILE VS. MOTILE/MOBILE SENSOR NETWORK

Total Number of Nodes	25	50	75	100	125	150
Mobility	9	23	40	44	41	33
Motility+Mobility	1	8	19	17	10	4

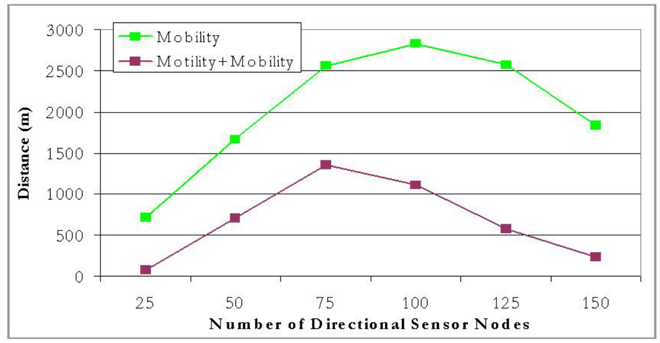

Figure 5. Total travel distance of directional sensor nodes for mobile and motile/mobile DSNs.

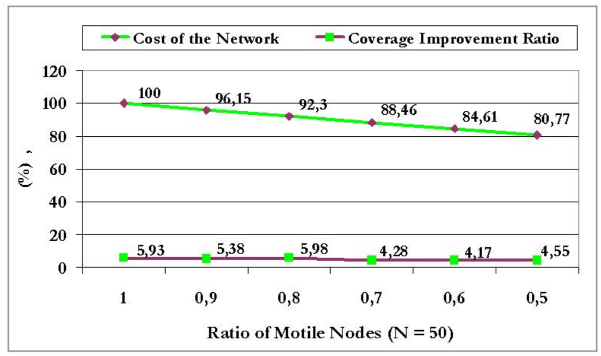

Figure 6. The correlation between the coverage improvement and the cost of the network in hybrid sensor networks

Figure 6 demonstrates the importance of hybrid deployment. Following Figure 6, even if a large number of deployed directional sensor nodes are stationary, the coverage gain ratio does not change too much if all the nodes were motile. As an example, in the scenario where the ratio of motile nodes is 60%, the total coverage ratio increases by 4.17%. Deploying the same scenario with all the sensor nodes being motile, causes the total coverage to increase by only 5.93%. Thus, with hybrid deployment, by acknowledging a coverage gain drop of 1%-2%, the deployment cost could be reduced by 20%.

V. CONCLUSION

In this study, we have presented the preliminary results of a Ph.D. thesis, which examines the effect of motility and mobility capabilities of the directional sensor nodes on the coverage improvement and the cost of the network. The proposed hybrid solution aims at maximizing the total coverage with minimum energy consumption after the initial deployment. Simulation results also show that deploying hybrid DSNs could balance the ratio between the deployment cost of network and the total coverage improvement.

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