This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

An Anti-Detection Moving Strategy for Mobile Sink

Zhou Sha, Jia-Liang Lu, Xu Li, Min-You Wu
Dept. of Computer science and Engineering, Shanghai Jiao Tong University
Shanghai, CHINA
shazhou@sjtu.edu.cn

***Abstract*—Sink mobility has attracted much research interests in Wireless Sensor Networks (WSNs), because it could provide energy saving and reduce latency during data collection. However, the mobile sink node is still a single point of failure in many WSNs applications, thus needs to be particularly protected against adversaries. We propose in this paper a moving strategy for the mobile sink which prevents tracking or detecting on it by adversaries during its data collection phase around the sensor field. Our moving strategy aims to selecting a trajectory for mobile sink node, which minimizes the total number of message communication from all static sensor nodes to the mobile sink node (including multi-hop relaying) and thereby reducing the possibility of being detected by the adversaries. We also employed a routing protocol on sensor nodes to forward the data to mobile sink node with shortest-path. Four strategies are evaluated in our simulation and the performance results show that our moving strategy we proposed achieves best goal and adapts well to the different deployment patterns.**

Keywords-Wireless sensor networks, mobile sink, moving strategy, anti-detection

I. INTRODUCTION

Wireless sensor networks (WSNs) are composed of a large number of static nodes with sensing and communication capabilities. Recently, it is point out in [1][11], that using mobile nodes can balance the workload of the nodes in the network for data gathering process, and thereby prolong the network lifetime to a great extent. Using mobile nodes is also a way to enhance the connectivity in disconnected or sparse networks [6]. Furthermore, mobile nodes can be used for enabling other network functionalities such as energy replenishment [4][14], coverage repair [17], and localization [15].

Due to the additional cost on mechanical components, a mobile sensor node is much expensive than static sensor nodes. Therefore, in many WSN applications, a large number of low-cost static sensor nodes are deployed while only a few mobile sink nodes are employed to collect data. Related to its particular roles in a WSN, a mobile sink node interests the adversary much more than static nodes. First, due to the high privilege of the sink node, the enemy system and compromised nodes will try to tracking on the mobile sink node [19]. Unfortunately, this threat has been neglected by most of the moving schema for the mobile sink node, which only focus on load balance. Some algorithms even make the sink node visit every sensor node deployed in the field. Such moving strategies make the detection on mobile sink node easier to adversaries. Second, the hostile node would be able to decode the package content once it detects the packets transmitted in its detection range. In [7], ZigZag, a new 802.11 receiver, was proposed to combat hidden terminals which could be easily used to improve the decode capability of a hostile and help to detect the mobile sink nodes through a number of received messages. In [9][10], the authors proposed a detection model to find the base station in the network topology using traffic analysis. Most of detection methods are based on the large amount of message relay or redundant transmission in the network. Therefore, it is critical to reduce the number of message communication to the mobile sink nodes.

To reduce the chance of being detected, we propose an anti-detection moving strategy for mobile sink nodes. According to our anti-detection schema, a mobile sink node can traverse through the WSN doing data collection with lower chance to be detected or tracked. We especially address how to hide the whole sensor network against the adversaries' detection by reducing the message communication during the data collection process. Furthermore, we employ a routing protocol on sensor nodes to forward the data to mobile sink node based on shortest-path. The paper is organized as follows: In section II, priori mobility models for mobile sink nodes are presented. Section III gives our problem statement with an analytical analysis. Our moving strategy for mobile sink nodes is presented in Section IV. Section V provides the simulations and the simulation results. Finally, Section VI concludes the paper.

II. RELATED WORK

The behaviors of mobile sink nodes have been investigated in some previous works. In our opinion, these works can be divided into three types: random, fixed, and adaptive strategy.

Random mobility, in [13][16], assuming all nodes are mobile, has proved that in some case it can improve the data capacity and throughput dramatically. However, absolute random walk for the WSNs is not suitable, since such moving behavior is unaware of potentially threatens like tracking or traffic analysis. Furthermore, another critical problem is that the worst-case latency of data transmission for random mobility cannot be bounded, which may require excessive data caching or bring high data drop rate.

For fixed mobility, in [2][3], the authors designed a system in which the mobile node traversed followed a fixed route. Such mobility has shown that it can reduce the communication energy consumption at the energy constrained nodes, and thereby increase useful network life. Contrary to the random mobility, the constraints of such moving behavior is too tight, thus it lacks flexibility and scalability. Once the network is transplanted to other circumstances, the moving path has to be redesigned. In addition, more complex path planning is researched in [1]. The authors designed a path planning algorithm to make the mobile device visit every sensor node. Although, such mobility can save much energy of the network with making most of the communications to become one-hop transmission, the network will suffer from severe latency due to the fact that the transmission rate is much faster than the moving speed of mobile devices. Especially, this problem will be aggravated with the size of the network scaling up. Another problem for such fixed path mobility is that it is very easy for the adversary nodes to track and detect the mobile sink node. Moreover, a visit-all-nodes path is much more vulnerable, since the hostile devices have lots of chances to detect and compromise the mobile node.

Adaptive mobility, which is also called autonomous moving strategy in some work, attracts more researches these years. In [12], the author had proved that finding an optimal moving position for the mobile sink nodes is an NP-hard problem. Also, the author proposed a heuristic algorithm to determine the direction and distance of moving. In [20], the author designed an autonomous moving strategy for the mobile sink node according to the residual energy of the static nodes, which is used to balance the network workload and thereby prolong the life of the network. However, most researches of such moving behavior is based on the event-driven application, such as detecting unbalanced network workload, targets moving or excessive energy consumption. None of them are used to enhance the security of the mobile sink or the static nodes.

III. PROBLEM STATEMENT

We assume the whole network is composed by a large number of battery-powered static sensor nodes and a high-powered mobile sink node. These static nodes are deployed in a square-shaped field. They constitute a dense, connected, multi-hop WSN. They harvest data from the area of interest covered by the network. The mobile sink node is responsible for collecting date from the static nodes. Both the sink node and the static nodes know their locations by GPS equipment or other self-configured localization algorithms [5]. Each static node sends their data to the sink node in a multi-hop manner.

To achieve the data collection task, the mobile sink node enters the sensor field at point S and leaves the sensor field at point D. The mobile sensor nodes are deployed by a terrain vehicle, but not a plane or a helicopter, thus S and D are located on the board of the sensor field. The traverse problem is defined as follow:

Definition 1: An object traverses through a field F on Axis i, if the projection of its trajectory on i equals to the projection of all points in F on i.

Definition 2: An object completely traverses through a field F, if it traverses through F on all F's dimensions.

According to the Definition 1, for a mobile sink node, S and D should locate on opposite edge of the square. To combat tracking algorithms aiming at sink node, the mobile sink cannot visit every static node in the field. The moving distance of such algorithms has no up-bound, which could give the adversaries infinite chance to track or attack. Therefore, from Definition 1 we further give a constraint on the mobility of sink node.

Definition 3: An object traverses "forward" through a field F on Axis i, if the projection of its trajectory on i has no overlap.

We give an example of traverse which doesn't meet the constraint in Figure 1. The trajectory of a mobile sink have an overlap between two dotted line on axis i. Thus, it doesn't meet the constraint.

Definition 4: An object completely traverses "forward" through a field F, if it traverses "forward" through F on all F's dimensions.

We consider a two dimension sensor field. Therefore, the mobile sink node traverses "forward" through the field on Axis x and y. In addition, for the data collection, the mobile sink node traverses in a move-stop manner. Between each two motions, the mobile sink node sojourns to make a moving decision while collecting data. For simplicity, we assume the moving distance of the mobile sink node is a predefined constant.

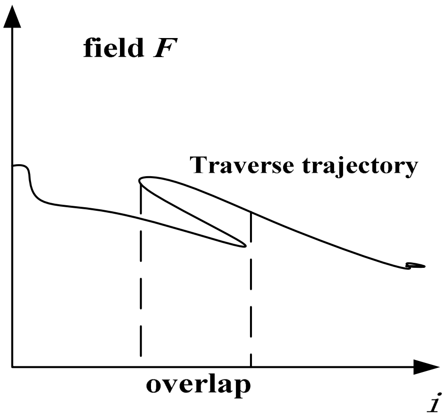

Figure 1. The projection of a traverse path on axis i has an overlap.

According to the Definition 4, we give our problem statement:

Problem 1: Find a trajectory for the mobile sink when it traverses "forward" through the sensor field, to minimize the possibility that the sensor network is detected by the adversaries.

Let us now, give some assumptions on adversary's detection. We assume that several adversary nodes are deployed randomly in the field to detect the message transmission of the covered field. And each static node is under detection of at least one adversary node. Thus each transmission will be detected by enemy with a probability $\wp$. Therefore, the probability $\mathcal{P}$ that none packet is detected is:

$$\mathcal{P} = (1 - \wp)^n \quad (1)$$

where n indicates the transmission occurred in the field. To combat detection of adversary nodes, we should maximize this probability $\mathcal{P}$ which is related to $\wp$ and n. However, $\wp$ in (1) is related to the density of the adversary nodes, both of which we cannot control. Thus, we can only increase the probability $\mathcal{P}$ by reducing the message transmitted (including multi-hop relaying) in the sensor field.

Here, we convert Problem 1 to Problem 2 according to the detection model.

Problem 2: Find a trajectory for the mobile sink when it traverses "forward" through the sensor field, to minimize the message communication in the sensor field.

Thus the goal of our anti-detection schema is to find a path for the mobile sink node to reduce n under the moving constraints.

IV. ANTI-DETECTION SCHEMA

We propose here Traverse Forward Through (TFT) moving strategy to reduce the number of message communication during the data collection phase, as to provide protection to the sensor network against detection. Our moving strategy makes the mobile sink node traverse "forward" through the field composed by static nodes in a move-stop manner. Before the sink node starts to move, the static nodes carry out a neighbor discovery process first. The discovery process aims at building the neighbor list for each static node. During the process of neighbor discovery, each static node broadcasts a message containing its ID and physical position. We assume that the transmission rate among the static nodes is much faster than the moving speed of mobile sink node. Thus the neighbor discovery phase is able to finish before the mobile sink node start to move.

Once the static node is connected with the mobile sink during its data collection process, it then uploads the neighbor information including the ID and the position to the mobile sink to help it to make moving decision based on the position information. The mobile sink node sets up a position coordinate system with the sojourn position as the origin and divides the coordinate system into four quadrants, as shown in Figure 3. Mobile sink node should select its next position in Quadrant IV according to the previous Definition 4. It also means the mobile sink node moves always towards this quadrant. The positions of all static nodes in the quadrant I, III and IV out of the communication range of mobile sink node are taken into account in the decision of next moving direction for mobile sink node. The static nodes in the quadrant II and those nodes that are one hop from the mobile sink node have no effect on the mobile sink node. That is because the number of their message communication to the mobile sink node cannot be further reduced in its next move.

In Figure 2, given a certain point B(x, y) on the arc of quadrant IV, the Euclidean distance between the point and one static node $\mathcal{S}_i(x_i, y_i)$ is

$$d_i = \sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2} \qquad (2)$$

Thus, the routing path length (in hops) l from $\mathcal{S}_i$ to B is approximately linear to d, $l \approx kd$, due to the assumption of a shortest path routing protocol[11]. Suppose the candidate nodes

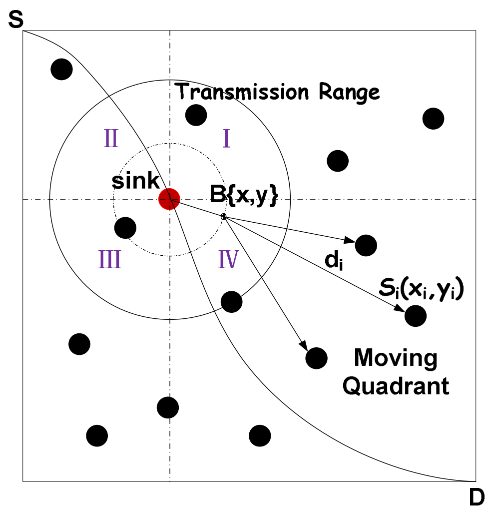

Figure 2. During one sojourn time of the mobile sink node, the sink node divides the square field into four quadrants. The candidate nodes calculate the distance to the point(x, y)

are $\{d_1, d_2, \cdots, d_n\}$, thus the summation of the Euclidean distance of all the candidate nodes is

$$\mathcal{D}(\mathcal{X}, \mathcal{Y}) = \sum_{i=1}^{n} d_i = \sum_{i=1}^{n} \sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2} \qquad (3)$$

Since the total number of message communication n is proportion to $\mathcal{D}(\mathcal{X}, \mathcal{Y})$, the problem is converted to calculate the minimum value of $\mathcal{D}(\mathcal{X}, \mathcal{Y})$.

$$\mathcal{D}(\mathcal{X}, \mathcal{Y})_{\min} = \sum_{i=1}^{n} \sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2} \qquad (4)$$

Subject to

$$\mathcal{X}^2 + \mathcal{Y}^2 = \mathcal{R}^2 \qquad (5)$$
$$\mathcal{X} \geq 0, \mathcal{Y} \geq 0$$

Replace $\mathcal{Y}$ in (4) with equation (5):

$$\mathcal{D}(\mathcal{X}) = \sum_{i=1}^{n} \sqrt{(x_i - \mathcal{X})^2 + \left(y_i - \sqrt{\mathcal{R}^2 - \mathcal{X}^2}\right)^2} \qquad (6)$$

So, our problem is converted to calculate the minimum value of $\mathcal{D}(\mathcal{X})$ when $\mathcal{X}$ is between 0 and R. Next we differentiate $\mathcal{D}(\mathcal{X})$ with respect to $\mathcal{X}$:

$$\frac{\partial \mathcal{D}(\mathcal{X})}{\partial \mathcal{X}} = \sum_{i=1}^{n} \frac{\partial \sqrt{x_i^2 + y_i^2 + \mathcal{R}^2 - 2x_i\mathcal{X} - 2y_i\sqrt{\mathcal{R}^2 - \mathcal{X}^2}}}{\partial \mathcal{X}} = \sum_{i=1}^{n} \frac{y_i \frac{\mathcal{X}}{\mathcal{Y}} - x_i}{\sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2}} \qquad (7)$$

To obtain the minimum extremum, we make (7) equals to 0:

$$\frac{\partial \mathcal{D}(\mathcal{X})}{\partial \mathcal{X}} = 0 \qquad (8)$$

$$\sum_{i=1}^{n} \frac{y_i}{\sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2}} \frac{\mathcal{X}}{\mathcal{Y}} = \sum_{i=1}^{n} \frac{x_i}{\sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2}} \qquad (9)$$

$$\frac{\mathcal{Y}}{\mathcal{X}} = \frac{\sum_{i=1}^{n} \frac{y_i}{\sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2}}}{\sum_{i=1}^{n} \frac{x_i}{\sqrt{(x_i - \mathcal{X})^2 + (y_i - \mathcal{Y})^2}}} \qquad (10)$$

When the moving distance $\mathcal{R}$ is much smaller than the distance between the static nodes and the mobile sink node (since when the mobile sink node make moving decision, it overlooks the static nodes in its transmission range), (10) can be converted to

$$\tan \eta = \frac{\mathcal{Y}}{\mathcal{X}} \approx \frac{\sum_{i=1}^{n} \frac{y_i}{|\mu_i|}}{\sum_{i=1}^{n} \frac{x_i}{|\mu_i|}} = \frac{\sum_{i=1}^{n} \sin \theta_i}{\sum_{i=1}^{n} \cos \theta_i} \qquad (11)$$

where $|\mu_i|$ is the norm of the vector from the coordinate of mobile sink node to the coordinate of the static node $\mathcal{S}_i(x_i, y_i)$. η is just the moving direction.

However, this solution is a stationary point, which means it might be a maximal extremum or a minimal extremum. From the curve diagram of $\mathcal{D}(\mathcal{X})$ when x is between 0 and R, we find that there are three extremum: (R, 0), (0, R) and $(R\cos\eta, R\sin\eta)$. If there are more static nodes in the quadrant I or III, the minimal extremum is (R, 0) or (0, R) and η is maximal extremum. In contrast, if there are more static nodes in the quadrant IV, η is minimal extremum, i.e. the local optimal moving direction.

To summarize, the mobile sink node takes into account the distance between the next sojourn point and other static sensor nodes to compute moving direction in every sojourn time when it traverses through the static network. To make the optimal direction between each two motions, the mobile sink node sets up a coordinate system with the current position as the origin and divides the system into four quadrants. According to forward rules, only the static nodes out of its transmission range in the quadrant I, III and IV have impacts on the moving direction. As a result, if the candidate nodes in the quadrant I or III are more than the other two, the mobile sink moves along the x-axis or y-axis. Otherwise, the mobile sink node uses equation (11) to calculate the optimal direction. The mobile sink node uses this moving strategy until it reaches the destination.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

V. PERFORMNCE EVALUATION

In this section we present the experimental performance results of our proposed anti-detection schema. We set up a 200m by 200m square shaped field and deploy 1 mobile sink node and 100, 150, 200, 250 and 300 static nodes respectively. The transmission radius of the static node is set at r=25m to ensure node connectivity with high probability at each of the above node density. The radius of the mobile sink node is set at r = 25m. The mobile sink node traverses through the field from position (0, 0) to (200, 200) using the moving strategy mentioned above.

To test the effectiveness and reliability of our moving strategy, we try different deployment of the static nodes. First is uniform deployment over the whole field. Second is asymmetrical random deployment, which is deploying 3/4 static nodes in the half part of the field, as shown in Figure 3.

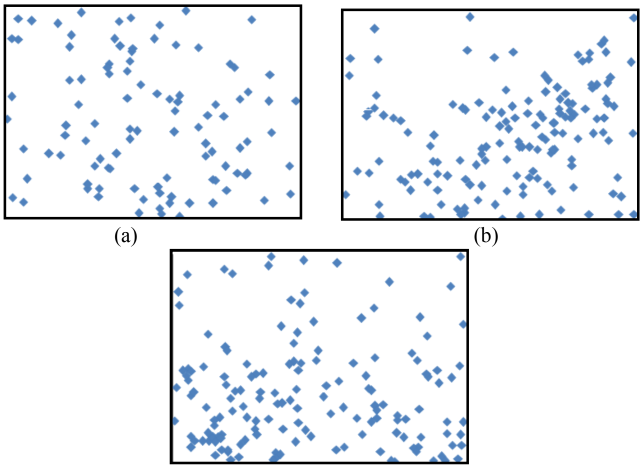

Figure 3. Different deployment of the static nodes: a). Uniform deployment over the whole filed; b). Most of the nodes deployed under the line y=x; c). Most of the of the nodes in the bottom field

We also implemented three other traverse paths to be compared with ours. The first moving strategy is random walk but still following the traverse constraints that the direction of moving is limited in the moving quadrant mentioned in section IV. The second moving strategy is traverse from (0, 0) to (200, 200) straightly, which is called diagonal move. The last strategy is traverse peripherally along the square field. The criterion of evaluation is the total number of the message communication of all static nodes n. It is worth noting that the minimum n leads to minimum detection probability that the mobile sink node is detected by adversaries

From the results showed in Figure 4, we can find that our moving strategy out-performs other moving strategies when sensor nodes are uniformly deployed over the whole field. The total number of the message communication of our moving strategy is nearly 30% less than the peripheral moving or random walk. However, the advantage of our moving strategy over the diagonal moving is slight. That is because when the static nodes are deployed uniformly in the field, the theoretic optimal path is the diagonal line. Thus, the results of two simulations are very similar.

However the gain of our schema over diagonal moving can be easily identified under asymmetrical deployment. Figure 5 shows that our moving strategy is better than three comparing moving strategy when most of the static nodes are deployed in the right-bottom part of the square field. From the diagram of simulation, we found that the moving path we obtained is between the diagonal line and the bottom and right boundary of the square field. This result indicates the validity of the principle of our moving strategy that traversing through the field where the nodes are denser protects better the sensor network. Figure 6 indicates that when most static nodes are deployed in the bottom part of the square field our moving strategy still achieve the best results among all moving strategies.

From the simulation results above, we proved that our moving strategy is the best among the four moving strategies. When the deployment of the static nodes is asymmetrical, the average improvement, compared with the diagonal moving, reaches about 20%. And the overall improvement, compared with the random walk and peripheral moving, is about 15% and 30% respectively. The simulation results also indicate that our moving strategy has the ability to "recognize" the deployment pattern and to adapt the moving path.

VI. CONCLUSION

In this paper, we propose an anti-detection moving strategy called TFT moving strategy for mobile sink node while achieving the data collection task. Different from other works on node mobility in WSNs, our goal is to reduce the possibility of detection on the sensor network and to protect the mobile sink against tracking. The mobile sink node uses greedy algorithm to choose an optimal direction during each sojourn time between two motions.

We have compared the random moving strategy, a fix diagonal traverse strategy, a peripheral moving strategy and our TFT moving strategy via simulation. The results show that our moving strategy achieves the smallest number of message communication among all moving strategies in different deployment pattern. It also provides the best adaptability than the other three moving strategies.

In terms of future work, we intend to study the sensitivity of the moving strategy to the density of the static node and the size of the whole networks to further evaluation the adaptability of our schema on the deployment pattern. We will also explore how a set of mobile sink nodes can be coordinated to further reduce the package transmission in the whole network and combat the detection of adversaries.

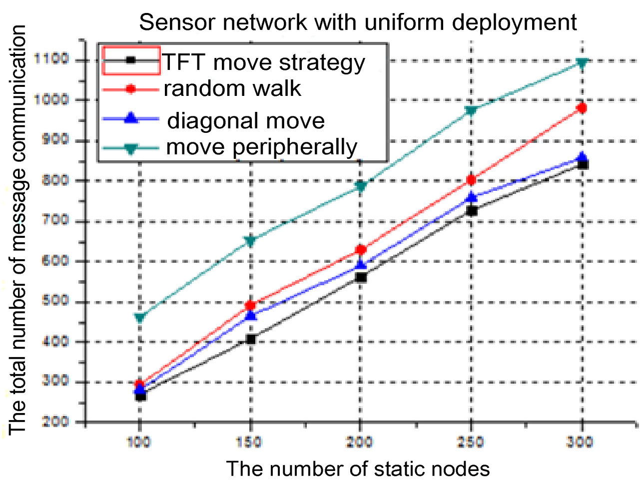

Figure 4. The simulation results of the four moving strategy when the static nodes are deployed uniformly. LHC moving strategy is the strategy proposed in section III.

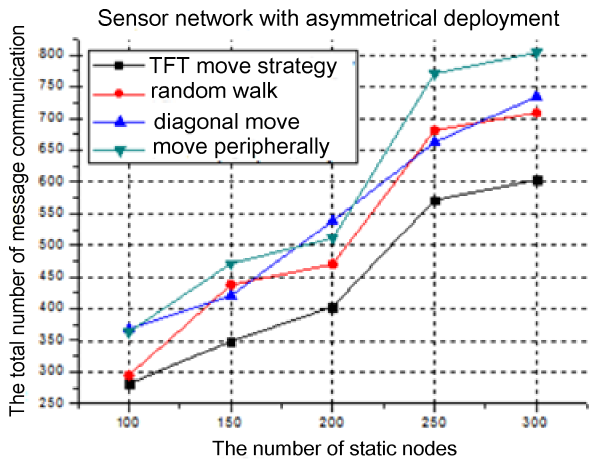

Figure 5. The simulation results of the four moving strategy when most of the static nodes are deployed under the line y = x.

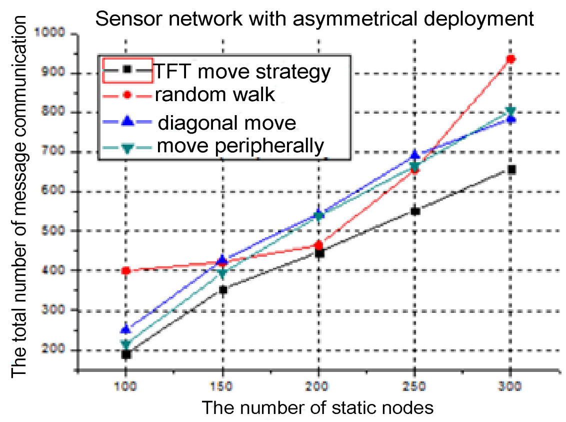

Figure 6. The simulation results of the four moving strategy when most of the static nodes are deployed in the bottom part of the field.

REFERENCES

[1] A. A. Somasundara, A. Ramamoorthy, and M. B. Srivastava, "Mobile element scheduling for efficient data collection in wireless sensor networks with dynamic deadlines," in Proceedings of the 25th IEEE International Real-Time Systems Symposium (RTSS '04), pp. 296–305, Lisbon, Portugal, December 2004.

[2] A. A. Somasundara, A. Kansal, D. D. Jea, D. Estrin, and M. B. Srivastava, "Controllably mobile infrastructure for low energy embedded networks," IEEE Transactions on Mobile Computing, vol. 5, no. 8, pp. 958–973, 2006.

[3] A. Kansal, A. A. Somasundara, D. D. Jea, M. B. Srivastava, and D. Estrin, "Intelligent fluid infrastructure for embedded networks," in Proceedings of the 2nd International Conference on Mobile Systems, Applications and Services (MobiSys '04), pp. 111–124, Boston, Mass, USA, June 2004.

[4] A. LaMarca, D. Koizumi, M. Lease, S. Sigurdsson, G. Borriello, W. Brunette, K. Sikorski, and D. Fox, "PlantCare: An Investigation in Practical Ubiquitous Systems," Proc. Fourth Int'l Conf. Ubiquitous Computing (UbiComp), 2002.

[5] T. He, C. Huang, B. M. Blum, J. A. Stankovic, and T. Abdelzaher, "Range-free localization schemes for large scale sensor networks," in *Proc. ACM Int. Conf. Mobile Computing and Networking (MOBICOM)* San Diego, CA, Sep. 2003, pp. 81-95.

[6] B. Zhang, G. Sukhatme, and A. Requicha, "Adaptive Sampling for Marine Microorganism Monitoring," Technical Report CRES-04-006, Center for Robotics and Embedded Systems, Univ. of Southern California, 2004.

[7] Gollakota, S. and Katinabi, D., "ZigZag Decoding: Combating Hidden Termals inWireless Networks", ACM SIGCOMM, 2008.

[8] J. Butler, "Robotics and Microelectronics: Mobile Robots as Gateways into Wireless Sensor Networks," Technulogy@Intel Magzine, May 2003.

[9] J. Deng, R. Han, and S. Mishra. Inrusion tolerance and anti-traffic analysis strategies in wireless sensor networks. In IEEE 2004 International Conference on Dependable Systems and Networks (DSN'04), Florence, Italy, June 2004.

[10] Jing Deng , Richard Han , Shivakant Mishra, Countermeasures Against Traffic Analysis Attacks in Wireless Sensor Networks, Proceedings of the First International Conference on Security and Privacy for Emerging Areas in Communications Networks, p.113-126, September 05-09, 2005

[11] J. Luo and J. P. Hubaux, "Joint mobility and routing for lifetime elongation in wireless sensor networks," in Proceedings of the 24th IEEE INFOCOM, Mar 2005.

[12] K. Akkaya, M. Younis, and M. Bangad, "Sink repositioning for enhanced performance in wireless sensor networks," Computer Networks, vol. 49, no. 4, pp. 512–534, 2005.

[13] M. Grossglauser and D.N.C. Tse, "Mobility Increases the Capacity of Ad Hoc Wireless Networks," IEEE/ACM Trans. Networking (TON), vol. 10, no. 4, Aug. 2002.

[14] M. Rahimi, H. Shah, G.S. Sukhatme, J. Heidemann, and D. Estrin, "Studying the Feasibility of Energy Harvesting in a Mobile Sensor Network," Proc. IEEE Int'l Conf. Robotics and Automation, 2003.

[15] R.K. Harle and A. Hopper, "Building World Models by Ray Tracing within Ceiling Mounted Positioning Systems," Proc. Fifth Int'l Conf. Ubiquitous Computing (UbiComp), 2003.

[16] S. Diggavi, M. Grossglauser, and D. Tse, "Even One-Dimensional Mobility Increases Ad Hoc Wireless Capacity," Proc. IEEE Int'l Symp. Information Theory (ISIT), 2002

[17] S. Ganeriwal, A. Kansal, and M. Srivastava, "Self-Aware Actuation for Fault Repair in Sensor Networks," Proc. IEEE Int'l Conf. Robotics and Automation (ICRA), Apr. 2004.

[18] S. Jain, R.C. Shah, G. Borriello, W. Brunette, and S. Roy, "Exploiting Mobility for Energy Efficient Data Collection in Sensor Networks," Proc. Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2004.

[19] S.L. Preston, D.V. Thiel, T.A. Smith, S.G. O'Keefe, and J.W. Lu. "Base-station tracking in mobile communications using a switched parasitic antenna array," IEEE Transactions on Antennas and Propagation, 46(6):841--4, Jun. 1998.

[20] Y. Bi, L. Sun, J. Ma, N. Li, I. Khan, and C. Chen, "Hums: An autonomous moving strategy in data gathering sensor networks," EURASIP Journal On Wireless Communication and Networking, 2007.

ACKNOWLEDGEMENT

This research was partially supported by NSF of China under grant No. 60773091, 973 Program of China under grant No. 2006CB303000, Key Program of National MIIT under Grants No. 2009ZX03006-001 and 2009ZX03006-004, Shanghai Post-Doc grant No.09R21413700.