Heterogeneous Wireless Sensor Network Deployment and Topology Control Based on Irregular Sensor Model

Chun-Hsien Wu[1] and Yeh-Ching Chung[1]

[1] Department of Computer Science, National Tsing Hua University,
Hsinchu 30013, Taiwan, R.O.C.
{chwu, ychung}@cs.nthu.edu.tw

Abstract. Heterogeneous wireless sensor network (heterogeneous WSN) consists of sensor nodes with different ability, such as different computing power and sensing range. Compared with homogeneous WSN, deployment and topology control are more complex in heterogeneous WSN. In this paper, a deployment and topology control method is presented for heterogeneous sensor nodes with different communication and sensing range. It is based on the irregular sensor model used to approximate the behavior of sensor nodes. Besides, a cost model is proposed to evaluate the deployment cost of heterogeneous WSN. According to experiment results, the proposed method can achieve higher coverage rate and lower deployment cost for the same deployable sensor nodes.

Keywords: Wireless sensor network, heterogeneous sensor deployment, topology control, sensor coverage, irregular sensor model.

1 Introduction

Wireless sensor network (WSN) is a key element of the pervasive/ubiquitous computing. With the advancement of manufacturing and wireless technologies, many feasible applications are proposed such as industrial sensor networks [4], volcano-monitoring networks [10], and habitat monitoring [11], etc. The heterogeneous WSN consists of sensor nodes with different abilities, such as various sensor types and communication/sensing range, thus provides more flexibility in deployment. For example, we can construct a WSN in which nodes are equipped with different kinds of sensors to provide various sensing services. Besides, if there are two types of senor nodes: the high-end ones have higher process throughput and longer communication/sensing range; the low-end ones are much cheaper and with limited computation and communication/sensing abilities. A mixed deployment of these nodes can achieve a balance of performance and cost of WSN. For example, some low-end sensor nodes can be used to replace high-end ones without degrading the network lifetime of WSN. Many research works have been proposed to address the deployment problem of heterogeneous WSN [3] [5].

To achieve a satisfying performance, the deployment of heterogeneous WSN is more complicated than homogeneous WSN. Deployment simulation is essential before actual installation of sensor nodes, since different deployment configurations can be tested without considering the cost of real node deployment. However, to reflect the behavior of WSN correctly is a major challenge of sensor nodes deployment simulation. In many research works, disk model is commonly used [6] [7] [8]. However, a fixed communication or sensing range is not practical to a realistic senor node. Moreover, node deployment in heterogeneous WSN has to consider the topology control between different types of sensor nodes. For example, to maintain a symmetric communication, the distance between high-end and low-end sensor nodes cannot be larger than the maximum communication range of the low-end one. Besides, if the sensor nodes have different detection range, the sensor coverage area of low-end node cannot be fully covered by the high-end node.

In this paper, a heterogeneous sensor deployment and topology control method is presented. It aims to deal with the deployment problem of heterogeneous sensor nodes with different communication and sensing range. In addition, an irregular sensor model is proposed to approximate the behavior of sensor nodes. According to experiment results, the proposed method can achieve higher coverage rate under the same deployable sensor nodes. Besides, the deployment cost is much lower with different configurations of sensor nodes.

The rest of the paper is organized as follows. In Section 2, previous works related to heterogeneous sensor deployment and irregular sensor model are addressed. In Section 3, the irregular sensor model and some definitions of heterogeneous WSN used in this paper are given. In Section 4, we present the details of heterogeneous sensor node deployment. Section 5 evaluates the performance of the proposed method under various scenarios. Finally, we conclude the paper in Section 6.

2 Related Work

The benefit of heterogeneous wireless sensor networks has been studied in many research works. Lee et al. [5] analyze heterogeneous deployments both mathematically and through simulations in different deployment environments and network operation models considering both coverage degree and coverage area. Experiment results show that using an optimal mixture of many inexpensive low-capability devices and some expensive high-capability devices can significantly extend the duration of a network's sensing performance. In [3], Hu et al. investigate some fundamental questions for hybrid deployment of sensor network, and propose a cost model and integer linear programming problem formulation for minimizing energy usage and maximizing lifetime in a hybrid sensor network. Their studies show that network lifetime can be increased dramatically with the addition of extra micro-servers, and the locations of micro-servers can affect the lifetime of network significantly. In addition, the cost-effectiveness analysis shows that hybrid sensor network is financially cost efficient for a large case.

In many research works [6] [7] [8], unit disk graph (UDG) is a commonly used sensor model to reflect the correct behavior of sensor node. It assumes the effective communication and sensing region of sensor node is a circle with fixed radius. However, a constant communication and sensing range is not practical for a realistic senor node. In [2], He et al., propose a model with an upper and lower bound on signal propagation. If the distance between a pair of nodes is larger than the upper bound, they are out of communication range. If within the lower bound, they are guaranteed to be within communication range. The parameter DOI (degree of irregularity) is used to denote the irregularity of the radio pattern. It is the maximum radio range variation per unit degree change in the direction of radio propagation. When the DOI is set to zero, there is no range variation, resulting in a UDG model. Zhou et al. [12] extended the previous DOI model as radio irregularity model (RIM) based on the empirical data obtained from the MICA2 and MICAZ platforms.

3 Preliminaries

3.1 Irregular sensor model

In this paper, an irregular sensor model is proposed based on the radio propagation model inspired from Radio Irregularity Model (RIM) [12] and degree of irregularity (DOI) [2]. The irregular sensor model assumes that the sensor node use the same radio propagation model for communication and sensing. For each sensor node, a radio propagation range is pre-defined and denoted as R_{def}, and the effective radio propagation range ($R_{effective}$) is decided by the normal (Gaussian) distribution with a mean of R_{def} and a standard derivation of DOI, where DOI represents for the degree of irregularity of $R_{effective}$.

Figure 1 illustrates the radio propagation range under different DOI. According to the "68-95-99.7 rule", about 99.7% of the values are within three standard derivations away from the mean (R_{def}) [9]. Thus we define the $R_{effective}$ is ranged from R_{def} – 3*DOI (R_{min}) to R_{def} + 3*DOI (R_{max}), and the relationship between R_{def}, R_{min}, and R_{max} is illustrated in Figure 2.

After the effective radio propagation range is calculated, we can use it to derive the radio strength model based on the simple transmission formula for a radio circuit made up of an isotropic transmitting and a receiving antenna in free space [1]:

$$P_r / P_t = A_r A_t / d^2 \lambda^2 . \quad (1)$$

where P_t is the power fed into the transmitting antenna at its input terminals, P_r is the power available at the output terminals of the receiving antenna, A_r (or A_t) is the effective area of the receiving (or transmitting) antenna, d is the distance between antennas, and λ is the wavelength. Suppose that P_t, A_r, A_t, and λ are constants, then the received radio power (P_r) is proportional to $1/d^2$. Thus, we define the radio strength of senor node n at point p as follows:

$$R(n, p) = (R_{effective} / d(n, p))^2 . \quad (2)$$

where $d(n, p)$ is the Euclidean distance between node n and point p. If $R(n, p) \geqq 1$, then there exists radio connection between node n and point p.

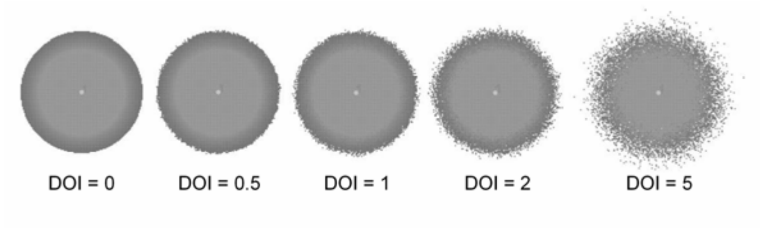


Fig. 1. The radio propagation range under different DOI.

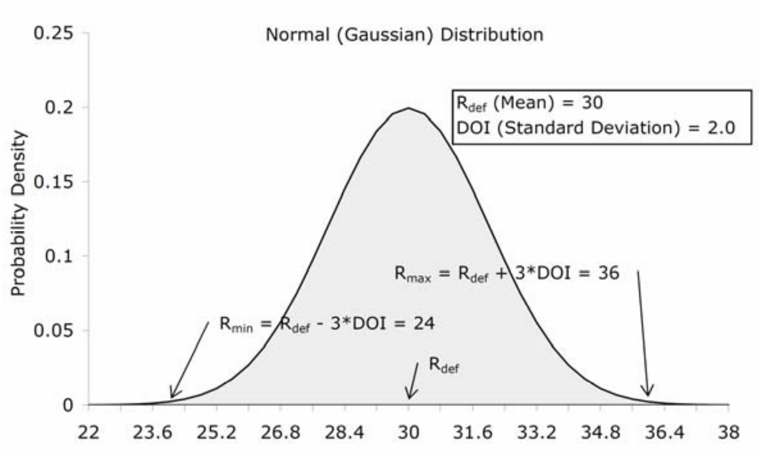


Fig. 2. The relationship between R_{def}, R_{min}, and R_{max}.

According to the definition of $R_{effective}$, we have the following observations:

1. If $d(n, p) < R_{min}$, $R(n, p)$ must be larger than 1.
2. If $d(n, p) > R_{max}$, $R(n, p)$ must be less than 1.
3. If $d(n, p) > R_{effective}$, the radio connection between two nodes cannot be guaranteed. Here we define "out of range" as $R(n, p)$ = *min_strength*, where *min_strength* is the minimum threshold of radio strength that guarantees radio connection between node n and point p, thus the maximum connectable distance between node n and point p is R_{max}/sqrt(*min_strength*).
4. Similarly, we define "too closed" as $R(n, p)$ = *max_strength*, where *max_strength* is the maximum acceptable radio strength for node n, thus the minimal distance between node n and point p is R_{min}/sqrt(*max_strength*).

The relationship between $R(n, p)$ and $d(n, p)$ is illustrated in Figure 3. In the Section 4, the proposed irregular sensor model will be used to select a proper sensor node location and calculate coverage rate.

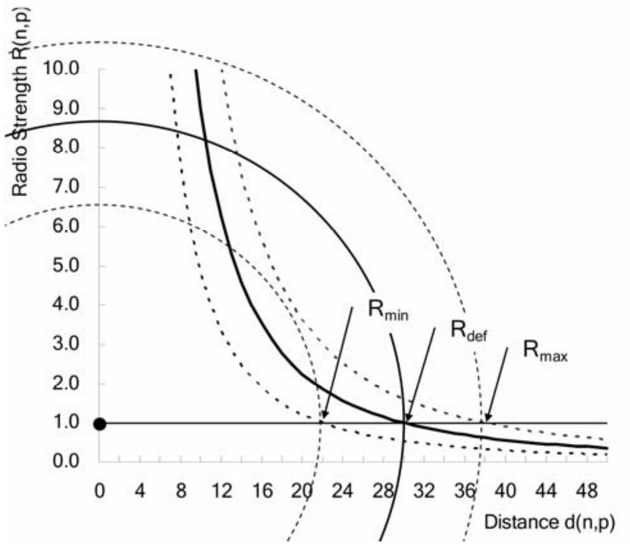


Fig. 3. The relationship between $R(n, p)$ and $d(n, p)$.

3.2 Some definitions of heterogeneous wireless sensor network

In this paper, we define a heterogeneous WSN that consists of three types of nodes: sink node, high-end senor node (N_H), and low-end senor node (N_L). Each node has the same communication model and two types of sensor nodes have the same sensing model. The difference between N_H and N_L is that the pre-defined communication and sensing range are different. The default communication and sensing range of N_H are defined as R_{CH} and R_{SH}, respectively. Similarly, R_{CL} and R_{SL} are denoted as the default communication and sensing range of N_L, where $R_{CH} > R_{CL}$, and $R_{SH} > R_{SL}$.

To evaluate the results of sensor node deployment, we define a deployment cost model as:

$$deployment\_cost = (\mathrm{Num}(N_H) * N_H\_cost + \mathrm{Num}(N_L)) \,/\, total\_coverage\_rate \,. \quad (\mathbf{3})$$

$$N_H\_cost = (R_{CH} + R_{SH}^2) \,/\, (R_{CL} + R_{SL}^2) \,. \quad (\mathbf{4})$$

where *deployment_cost* is calculated as the total cost of deployed sensor nodes divided by the *total_coverage_rate* produced by these sensor nodes, and N_H_cost is the difference of sensor node cost between N_H and N_L. The sensor node cost is determined by two factors: communication distance and coverage area of sensor, represented by R_c and R_s^2 respectively. The calculation of *total_coverage_rate* is based on the irregular senor model described in Section 3.1. At first, the deployment area is filled with grid points. For a senor node N, its *coverage_rate* at grid point p is based on Equation (2) in Section 3.1:

$$coverage\_rate = (effective\_range \,/\, d(N, p))^2 \,. \quad (5)$$

where *effective_range* is a random value with normal distribution between $\min(R_S)$ and $\max(R_S)$. After all sensor nodes are processed, each grid point will keep the highest coverage rate but not exceed one. The *total_coverage_rate* is equal to the sum of *coverage_rate* divided by the number of grid points.

4 Heterogeneous Sensor Deployment

In this section, a heterogeneous sensor deployment method is proposed. Given a deployment area and the upper bound of deployable high-end and low-end sensor nodes, the objective is to construct a communication-connected sensor network, in which high-end and low-end sensor nodes are deployed uniformly to achieve high coverage rate. In the initialization step, a deployment area is initialized base on the configuration file. In the neighbor-info collection step, starting from the sink node, the information of adjacent sensor nodes within the communication range is collected. It can be used to decide the deployment ratio of high-end and low-end sensor nodes. In the candidate generation step, candidate positions are generated according to topology control policies, and a scoring mechanism based on the irregular sensor model is applied to each candidate. At least, a new sensor node with the most coverage gains is deployed while maintaining the communication connectivity. The number of deployable sensor nodes is limited by the pre-defined quota of sink/sensor node. If the quota is reached, then a deployed sensor node with available quota will be selected. The deployment process will be repeated until the upper bound of deployable sensor nodes is reached or no suitable place available to add a sensor node. In the following, we will describe each deployment step in details.

4.1 Initialization step

In this step, a sensing area is generated from a given configuration file. This file includes the size of deployment area, the location of pre-deployed sink node and sensor nodes, the upper bound of deployable high-end and low-end sensor nodes, and default value of parameters defined in Section 3. These parameters include the default communication and sensing distance of high-end/low-end sensor node (R_{CH}, R_{SH}, R_{CL}, and R_{SL}), the degree of irregular (DOI), and the threshold of radio strength (*max_strength* and *min_strength*). Then the maximum/minimum value of the effective radio propagation range ($R_{effective}$) is calculated for each type of node according to the given DOI. For example, if the default R_{CH} = 30 and DOI = 2.0, then the maximum effective communication distance $\max(R_{CH}) = R_{CH} + 3*DOI = 36$ and the minimum effective communication distance $\min(R_{CH}) = R_{CH} - 3*DOI = 24$.

Thus, the effective communication distance of high-end sensor node fits a normal distribution ranged from 24 to 36.

4.2 Neighbor-info collection step

At first, a center node for deployment is selected. The selection of eligible center node is starting from sink node, and then expanding to all deployed sensor nodes. The criterion of eligible node is based on the available quota for node deployment, which is limited by the degree of node defined in the configuration file. The number of deployed high-end and low-end sensor nodes within minimum effective communication distance is denoted as Neighbor(N_H) and Neighbor(N_L). They will be used to decide the deploy ratio of high-end and low-end sensor nodes. Suppose the number of deployable high-end and low-end nodes is denoted as Remain(N_H) and Remain(N_L), respectively. Then the limit numbers of deployable high-end and low-end senor node are represented as Equation (6) and (7):

$$\text{Deploy}(N_H) = \text{limit degree of center node} * \text{Remain}(N_H) / (\text{Remain}(N_H) + \text{Remain}(N_L)) \ . \quad (6)$$

$$\text{Deploy}(N_L) = \text{limit degree of center node} - \text{Deploy}(N_H) \ . \quad (7)$$

If Deploy(N_H) $\leqq$ Neighbor(N_H), then Deploy(N_H) = 0, means that the number of high-end sensor nodes is sufficient. At last, if Deploy(N_H) + Deploy(N_L) > 0, then the following deployment step will be processed, otherwise, the deployment process for current center node will be terminated and restarted on the next eligible node.

4.3 Candidates generation step

In this step, the candidate positions for each type of the sensor node will be generated separately. In heterogeneous sensor node deployment, the symmetric connection must be maintained. It means that the distance between two sensor nodes cannot larger than the maximum communication distance of the low-end one. Besides, the overlap of sensor coverage area between two senor nodes has to be considered to prevent the sensor coverage area of low-end node to be fully covered by the high-end node, which means no coverage gains. In the following, we will discuss the requirement to produce coverage gains while maintaining symmetric connection under different conditions:

– Case I: $R_{CH} > R_{SH}$ and $R_{CL} > R_{SL}$

In this case, the communication distance is larger than sensing range. Figure 4(a) illustrates the condition when a low-end node N_L is added to a high-end sensor node N_H. For N_L, if $d(N_H, N_L) < R_{CL}$, then the symmetric connection is established, and we said that these two nodes are communication-connected. If $d(N_H, N_L) \leqq (R_{SH} - R_{SL})$, then the sensor coverage area of N_L is fully covered by N_H, which means no coverage gains. By combining these observations, if two nodes are communication-connected and have coverage gains, then the distance between two nodes is:

$$(R_{SH} - R_{SL}) < d(N_H, N_L) < R_{CL} \ . \quad \textbf{(8)}$$

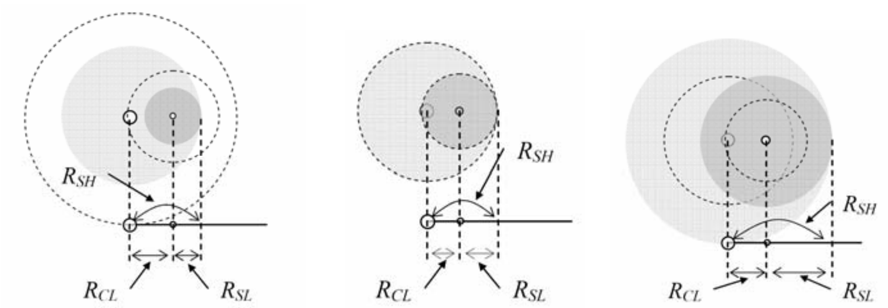
Thus, if we want to produce coverage gains while maintaining symmetric connection when deploying a new sensor node, the following condition must be satisfied:

$$R_{CL} - (R_{SH} - R_{SL}) > 0 \ . \quad \textbf{(9)}$$

– Case II: $R_{CH} = R_{SH}$ and $R_{CL} = R_{SL}$

From Figure 4(b), the requirement of communication-connected deployment with coverage gains can be derived from Equation (9) by replacing R_{CL} with R_{SL}:

$$2\ R_{SL} > R_{SH} \text{ or } 2\ R_{CL} > R_{CH} \ . \quad \textbf{(10)}$$



(a) $R_{CH} > R_{SH}$ and $R_{CL} > R_{SL}$ (b) $R_{CH} = R_{SH}$ and $R_{CL} = R_{SL}$ (c) $R_{CH} < R_{SH}$ and $R_{CL} < R_{SL}$

Fig. 4. Sensor node connection and coverage under different conditions

– Case III: $R_{CH} < R_{SH}$ and $R_{CL} < R_{SL}$

From Figure 4(c), we can find that the requirement of communication-connected deployment with coverage gains is identical to Case I.

Based on above results, candidate position is generated by the following topology control policies:

1. If a N_H is selected for node deployment, then the candidate positions of high-end/low-end senor nodes must be within the minimum effective communication distance of high-end/low-end senor node. That is, $d(N_H$, candidate position of high-end node) $\leqq$ min(R_{CH}), and $d(N_H$, candidate position of low-end node) $\leqq$ min(R_{CL}).

2. If a N_L is selected for node deployment, then the candidate positions of two types of sensor nodes must be within the minimum effective communication distance of low-end senor node. That is, $d(N_H$, candidate position of high-end/low-end node) $\leqq \min(R_{CL})$.
3. If $d(N_H$, candidate position of low-end node) $\leqq (R_{SH} - R_{SL})$, then this candidate position is discard because the sensor coverage area will be fully covered by N_H.
4. The minimum distance between candidate position and deployed nodes is defined as R_{min}/sqrt(*max_strength*), where $R_{min} = \min(R_{CH})$ or $\min(R_{CL})$ is the minimum effective communication distance of sensor node. It can prevent the deployed sensor nodes are too closed.

4.4 Scoring step

After candidate positions are generated for different types of sensor nodes, a scoring mechanism to each position is defined as follows: *total_score* = *connection_score* + *coverage_score*. The *connection_score* is the distance between candidate position and center node. The *coverage_score* of candidate position is defined as the coverage gains when a sensor node is deployed at the candidate position. The calculation of coverage gains is described as follows: At first, a square around center node with edge length = 2*max(R_S) is filled with grid points. Based on Equation (5) in Section 3.2, the total coverage rate produced by deployed sensor nodes is denoted as *base_coverage_rate*. Next, the total coverage rate with the contribution of candidate position is denoted as *target_coverage_rate*. Thus the *coverage_score* of candidate position = *target_coverage_rate* - *base_coverage_rate*.

4.5 Sensor addition step

After all candidate positions are scored, the candidate with the highest score is selected to deploy a new sensor, which has the most coverage gains while maintaining the communication connectivity to center node. If the deploy quota of current center node is reached, the next deployed sensor node with available quota will be selected. The deployment process will be repeated until the upper bound of deployable sensor nodes is reached or no suitable place available to add a sensor node.

5 Experiments

In this section, we evaluate the performance of the proposed sensor deployment method by comparing sensor coverage rate and deployment cost with several sensor node configurations. A simulation tool written in C++ language is running on an IBM eServer 326 (AMD Opteron 250 * 2 and 1GB memory). The deployment area is a 2-D square with 500 × 500 units. A sink node is deployed at (200, 200). The total number of deployable sensor nodes is ranged from 60 to 360. Other parameters are defined as follows: DOI = 2.0, *max_strength* = 1.2 and *min_strength* = 0.8.

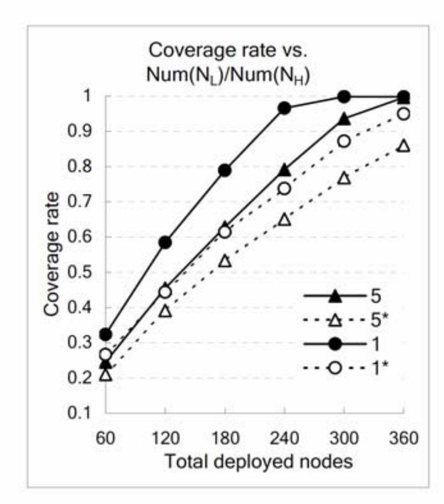


Fig. 5. Coverage rate of Test Case I

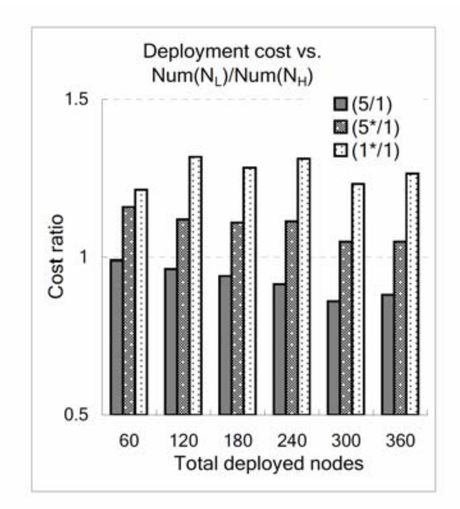


Fig. 6. Deployment cost of Test Case I

Test Case I is the coverage rate and deployment cost under different deployment ratio, where Num(N_L):Num(N_H) = 5:1 or 1:1. Besides, the ratio of communication/sensing range between N_H and N_L (R_H : R_L) is 1.5:1, and the ratio of communication and sensing range for N_H / N_L (R_C : R_S) is 1.5:1. We also compare the results with sensor deployment without topology control (case 2* and 5*). The deployment without topology control is based on the same deployment method, but it omits the topology control policies described in Section 4.3. The experiment results are illustrated in Figure 5 and Figure 6. In Figure 6, we compare the deployment cost of different cases (5, 5*, and 1*) with case 1 (denoted as 5/1, 5*/1, and 1*/1). With the help of topology control, the proposed method has higher coverage rate in comparison of the deployment method without topology control. It can be found lower deployment ratio can achieve higher coverage rate with the help of more high-end nodes. In addition, the reduction of deployment cost is significant for the deployment method with topology control. When deployment ratio is 5:1, it has higher coverage rate and lower deployment cost than the deployment method without topology control under the same deployment ratio.

Test Case II is the coverage rate and deployment cost under different ratio of the communication/sensing range between N_H and N_L (R_H : R_L), where R_{CH} : R_{SH} = R_{CL} : R_{SL} = 1.5:1, and deployment ratio of N_H and N_L is fixed to 5:1. Other configurations are identical to the Test Case I. Figure 7 and Figure 8 are experiment results. If R_H /R_L = 1, it can be regarded as homogeneous deployment since both N_H and N_L have the same communication and sensing range. With the help of high-end sensor nodes, the heterogeneous deployment can get higher coverage rate, but the homogeneous deployment has lower deployment cost. The deployment method without topology control still has higher deployment cost under the same ratio of R_H and R_L.

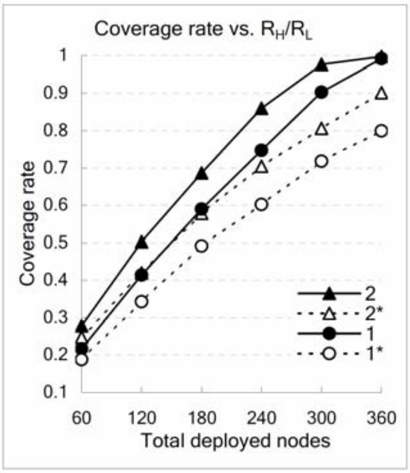


Fig. 7. Coverage rate of Test Case II

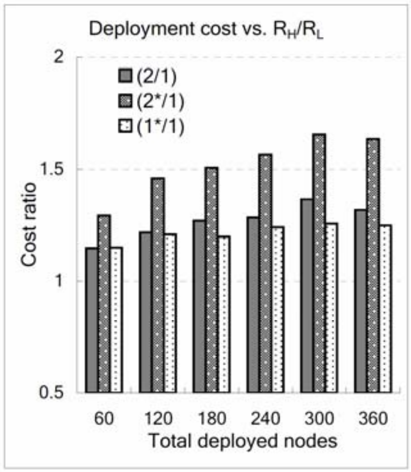


Fig. 8. Deployment cost of Test Case II

6 Conclusions

In this paper, we propose a heterogeneous WSN deployment method based on irregular sensor model. It aims to deal with the deployment problem of heterogeneous sensor nodes with different communication and sensing range. In addition, an irregular sensor model is proposed to approximate the behavior of sensor nodes. The deployment process is starting from sink node, and new nodes are deployed to the region centered with it. In neighbor-info collection step, the information of adjacent sensor nodes is used to decide the deployment ratio of different types of sensor nodes. In the scoring step, a scoring mechanism based on the irregular sensor model is applied to candidate positions. At least, a new sensor node is placed to the position with the most coverage gains while maintaining the communication connectivity to center node. Above process is running repeatedly until all eligible sensor nodes are processed.

According to experiment results, the proposed method can achieve higher coverage rate under the same deployable sensor nodes. Besides, the deployment cost is much lower with different configurations of sensor nodes. In the future work, a sensor node model considering environmental factors and individual behavior is needed. Besides, considering the interactions between different types of sensors is important. At least, the proposed method will be extended as the topology control protocol for heterogeneous WSN.

Acknowledgments. The work of this paper was partially supported by National Science Council and Ministry of Economic Affairs of the Republic of China under contract NSC 95-2221-E-007-018 and MOEA 95-EC-17-A-04-S1-044.

References

1. Friis, H.T.: A Note on a Simple Transmission Formula. In Proceedings of the IRE, Vol. 34, No. 5, (1946) 254- 256
2. He, T., Huang, C., Blum, B. M., Stankovic, J. A., and Abdelzaher, T.: Range-free localization schemes for large scale sensor networks. In Proceedings of the 9th Annual international Conference on Mobile Computing and Networking (MobiCom). (2003) 81-95
3. Hu, W., Chou, C.T., Jha, S., and Bulusu, N.: Deploying Long-Lived and Cost-effective Hybrid Sensor Networks. Elsevier Ad-Hoc Networks, Vol. 4, Issue 6. (2006) 749-767
4. Krishnamurthy, L., Adler, R., Buonadonna, P., Chhabra, J., Flanigan, M., Kushalnagar, N., Nachman, L., and Yarvis, M.: Design and deployment of industrial sensor networks: experiences from a semiconductor plant and the North Sea. In Proceedings of the 3rd international conference on Embedded networked sensor systems (SenSys). (2005) 64-75
5. Lee, J.J., Krishnamachari, B., Kuo, C.C.J.: Impact of Heterogeneous Deployment on Lifetime Sensing Coverage in Sensor Networks (IEEE SECON). (2004)
6. Li, L., Halpern, J. Y., Bahl, P., Wang, Y.-M., and Wattenhofer, R.: Analysis of cone-based distributed topology control algorithms for wireless multi-hop networks. In Proceedings of ACM Symposium on Principle of Distributed Computing (PODC). (2001)
7. Li, X.-Y., Wan, P.-J., Wang, Y., and Frieder, O.: Sparse power efficient topology for wireless networks. In Proceedings of IEEE Hawaii International Conference on System Sciences (HICSS). (2002)
8. Ramanathan, R. and Rosales-Hain, R.: Topology control of multihop wireless networks using transmit power adjustment. In Proceedings of the 20th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM). (2000)
9. Wikipedia contributors, “Normal distribution,” Wikipedia, The Free Encyclopedia. (http://en.wikipedia.org/w/index.php?title=Normal_distribution&oldid=93201679)
10. Werner-Allen, G., Lorincz, K., Welsh, M., Marcillo, O., Johnson, J., Ruiz, M., and Lees, J.: Deploying a Wireless Sensor Network on an Active Volcano. IEEE Internet Computing 10(2) (2006) 18-25
11. Xu, N.: A Survey of Sensor Network Applications. University of Southern California. (http://enl.usc.edu/~ningxu/papers/survey.pdf)
12. Zhou, G., He, T., Krishnamurthy, S., and Stankovic, J.: A. Models and solutions for radio irregularity in wireless sensor networks. ACM Trans. Sen. Netw. 2(2) (2006) 221-262