

# Impact of Heterogeneous Deployment on Lifetime Sensing Coverage in Sensor Networks

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**Abstract**— While most research on wireless sensor networks has focused on the deployment of large numbers of cheap homogeneous sensor devices, in practical settings it is often feasible to consider heterogeneous deployments of devices with different capabilities. Under prescribed cost constraints, we analyze such heterogeneous deployments both mathematically and through simulations, and show how they impact the coverage aging process of a sensor network, *i.e.*, how it degrades over time as some nodes become energy-depleted. We derive expressions for the heterogeneous mixture of devices that optimizes the lifetime sensing coverage in a single-hop direct communication model. We then investigate a multi-hop communication model through simulations, and examine the impact of heterogeneity on lifetime sensing coverage and coverage aging both with and without data aggregation. Our 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.

## I. INTRODUCTION

Wireless sensor networks consist of large number of low-cost devices to gather information from the diverse kinds of physical phenomenon. Numerous applications have been proposed and discussed including military surveillance, structural monitoring, and habitat monitoring [1], [2], [3]. For these sensor network applications, most research has discussed problems in a deployment of large number of low-cost homogeneous devices. However, it is often feasible to consider the deployment of heterogeneous devices with different capabilities.

In a heterogeneous deployment, devices with high capability can be considered to increase the quality and quantity of data processing inside network, and extend network lifetime through high energy capacity. On the other hand, higher capabilities including a large amount of equipped energy, high processing power and memory capacity, and longer sensing range, would increase the cost of the device. Hence, under prescribed cost constraints, increasing the number of high-cost devices may reduce a large number of low-capacity devices, which would affect sensing coverage performance such as sensor node density, coverage degree, or coverage area. There would exist advantages and disadvantages of deploying high-cost devices under total cost constraints. Our goal is to evaluate the effect of heterogeneous deployments on sensing coverage and the trade-off between initial coverage and the duration of network sensing operations.

Sensing coverage represents both the spatial extent and the degree to which the target phenomenon can be observed. *Sensing coverage area* is the spatial extent of network covered by sensors, which indicates the breadth of sensing coverage. On the other hand, *sensing coverage degree* means the number of sensors that cover a target object, which implies the depth of sensing coverage. It also reflects the density of sensor nodes as well as the reliability of monitored data from sensors in a certain area. For example, if two deployments have the same size of covered area but have different coverage degrees, the higher coverage degree deployment can extract more fine spatial information from the field.

Coverage area and degree would be varied with different mixtures of heterogeneous deployments depending on deployment conditions. In addition, the deployment of high capability nodes affects the energy depletion of other low-cost sensors, which results in the different coverage (area and degree) aging processes, *i.e.*, how coverage of a network degrades over time as nodes become energy-depleted, which is also dependent on the communication modes: single-hop and multi-hop. Some deployments may show faster coverage area loss rate, and some may have constant and uniform coverage degree in the remaining covered area over time, and other deployments may present the non-uniform coverage degree and slow covered area loss rate. These aging phenomena of coverage are also examined in our work.

In this paper, we analyze heterogeneous deployments both mathematically and through simulations in different network deployment environments and network operation models considering both coverage degree and coverage area. First, in analysis of single-hop communication case with evenly divided network area by the number of high-cost sensors, we derive expressions for the heterogeneous device deployment that maximizes the lifetime sensing coverage. Then, we investigate multi-hop communication model with and without data aggregation through simulations, in which nodes are randomly distributed. Analysis and simulation results show that optimal heterogeneous deployment can significantly enhance the duration of network operation and total lifetime sensing coverage information. In addition, different mixture of heterogeneous deployments and communication modes show different coverage aging patterns over time, which would affect the network performance over time, as well as re-deployment decisions.

The rest of this paper is organized as follows. In Section II, we discuss the related work on heterogeneous sensor network, coverage and network lifetime. In Section III, the system model for analysis is presented, including device and cost models, as well as coverage and energy consumption models. Next, we analyze the lifetime sensing coverage with heterogeneous devices in single-hop direct communication model considering various factors in Section IV. We provide the simulation results for multi-hop communication in Section V. Finally, we conclude the paper with future work in Section VI.

## II. RELATED WORK

Heterogeneous sensor deployment has been discussed in [4], [5], and [6] with consideration of deployment cost. Both studies in [4] and [5] focus on minimizing the total deployment cost while guaranteeing certain requirements. Chakrabarty *et al.* [4] present a solution for minimizing the cost of heterogeneous sensor deployment with complete coverage of the sensor field. They formulate an integer linear programming problem to solve the cost minimization problem in grid-based sensor deployment network. They do not consider the energy consumption of node and the communication in the network. Thus, the lifetime of heterogeneous sensor deployment is not discussed in their study. Mhatre and Rosenberg [5] provide the optimal heterogeneous sensor deployment that minimizes the deployment cost in different communication modes. In their model, the cost of the cluster head device is determined by the amount of initial battery energy, which depends on the number of cluster members and communication mode. They do not consider the sensing coverage and aging process over time. Kumar *et al.* [6] present the hierarchical network system with heterogeneous devices that have different capabilities. They show that partitioning of computation task with heterogeneous devices enhances the network performance compared to homogeneous node deployment.

Energy consumption model and the corresponding network lifetime analysis have been provided in [7], [8]. Heinzelman *et al.* [7] present the optimum number of clusters based on the energy consumption analysis and propose an energy-efficient clustering protocol. In their work, energy consumptions in different communication schemes are compared. They discuss the total energy required for the communication within the cluster, which provides the basis for the analysis of optimum number of clusters. Bhardwaj and Chandrakasan [8] derive the upper bounds on network lifetime based on the sensor role assignment that considers the topology and aggregation. They use the optimization model to compute the maximum lifetime of sensor network. Neither studies deals with the heterogeneous deployment and coverage problem.

Coverage in sensor network has been discussed in several work including [9], [10], [11], [12], [4]. Meguerdichian *et al.* [9] present a coverage metric that indicates the quality of service provided by sensor network. In addition, they provide the algorithm to calculate the worst-case and best-case coverage. Wang *et al.* [10] discuss the relation between

TABLE I  
SUMMARY OF NOTATION

$H$	Type H sensor: High cost sensor used as a sink
$L$	Type L sensor: Low cost sensor
$C_{tot}$	Total cost constraint
$C_i$	Cost for type $i$ sensor
$n_i$	Number of type $i$ sensor
$N_L^*$	Number of type $L$ sensors in homogeneous deployment
$R_i$	Sensing range radius of type $i$ sensor
$E_L$	Initial battery energy of type $L$ sensor
$E_1$	Non-radio range related energy dissipation per round
$E_2$	Radio range related energy dissipation per round
$S_d$	Sensing coverage degree
$S_a$	Sensing coverage area
$S_{tot}$	Total sensing coverage over entire network area
$S_{life}$	Total sensing coverage throughout the network lifetime
$T_d$	Network lifetime
$d_{max}$	Maximum distance from the closest sink

coverage and connectivity, and present the protocol that can maintain the desired degree of coverage dynamically inside the network. Shakkottai *et al.* [11] provide the bounds on the probability that every point of network area is covered and all nodes are connected given unreliable sensors deployed in a grid network. They also do not consider the network aging due nodes' energy depletion.

The key difference between our work and these prior studies is that we focus on identifying the impact of heterogeneous deployment on the lifetime sensing coverage and coverage aging process considering various deployment conditions and factors.

## III. SYSTEM MODEL

In this section, we present the preliminary system model for the analysis of the lifetime sensing coverage in heterogeneous network, which will be discussed in Section IV.

### A. Device and Cost Model

We assume that the heterogeneous network consists of two types of sensor devices: high-cost device ( $H$ ) and low-cost device ( $L$ ). High-cost device is used as a sink that gathers data from type  $L$  sensors in the network. The number of devices is determined from the total cost constraint ( $C_{tot}$ ) as

$$C_{tot} \geq n_H C_H + n_L C_L \quad (1)$$

where  $n_H$  and  $n_L$  are the numbers of each type of devices, and  $C_H$  and  $C_L$  are the costs for each device. Total cost is represented as

$$C_{tot} = C_H + N_L^* C_L \quad (2)$$

where  $N_L^*$  is the maximum number of  $L$  sensors that can be deployed in a homogeneous network with one sink. Since the coverage is determined by the number of sensors, we express the prescribed total cost constraint with  $N_L^*$  and the cost ratio in this paper. When more  $n_H$  are to be deployed in the network,  $n_L$  is determined by the cost constraint given (1) and (2) as

$$n_L = N_L^* - \frac{C_H}{C_L}(n_H - 1) \quad (3)$$

The device cost would be determined by several factors including equipped battery energy ( $E$ ), sensing range ( $R$ ),

reliability factor ( $\eta$ ), and others ( $M$ ) including processing power and memory capacity.

$$C_i = c_1 E_i + c_2 R_i + c_3 \eta_i + c_4 M_i$$

where  $C_i$  is the cost for type  $i$  device. In this paper, we only consider the overall device cost ratio between  $H$  and  $L$  for the analysis. Regarding the energy capacity of type  $H$  device, we assume that  $H$  is initially equipped with enough energy capacity that allows  $H$  to function as a sink till all  $N_L^*$  nodes die due to energy depletion. Number of type  $L$  sensors is maximum when one sink is deployed. Since the number of type  $L$  sensors per one sink decreases as  $n_H$  increases, the energy consumption rate of  $H$  becomes smaller.

### B. Sensing Coverage Model

In order to evaluate sensing coverage with heterogeneous deployments, we use *total sensing coverage*, which represents total information that can be extracted from all functioning sensors in a network area. This total sensing coverage ( $S_{tot}$ ) is defined as the sum of sensing coverage of each sensor.

$$S_{tot} = \sum_{i=1}^n \pi R_i^2$$

where  $n$  is the total number of sensors including sinks, and  $R_i$  is the sensing range of a sensor  $i$ . Total sensing coverage ( $S_{tot}$ ) implies not only sensing coverage area ( $S_a$ ), but also sensing coverage degree ( $S_d$ ). In analysis with uniformly distributed sensors, overlapping sensing coverage among neighboring sensors are represented with sensing degree. This sensing degree is incorporated in our analysis of single-hop heterogeneous deployments.

$$S_{tot} = S_d S_a \quad (4)$$

*Sensing coverage degree* ( $S_d$ ) is the average number of sensors that cover any point of network area, which can indicate node density and the degree of information in the fixed area. If we increase the number of sensors with constant sensing range in a fixed area, a denser node placement and correspondingly higher coverage degree can be achieved. This higher density allows more precise and finer-grained spatial information, and the higher degree provides more reliable data processing and decision against possible faulty information or unreliable sensors. Desirable coverage degree and node density in a network would mainly depend upon the application and the event characteristics. *Sensing coverage area* ( $S_a$ ) is defined as the size of network area that is covered by at least one functioning sensor. We examine the lifetime sensing coverage with both fixed coverage degree and fixed coverage area deployment cases in Section IV.

Using (3), total sensing coverage is expressed with the

number of sinks and sensing range as follows.

$$\begin{aligned} S_{tot}(n_H) &= n_H \pi R_H^2 + n_L \pi R_L^2 \\ &= \pi \left( n_H R_H^2 + \left( N_L^* - \frac{C_H}{C_L} (n_H - 1) \right) R_L^2 \right) \\ &= \pi \left( -\left( R_L^2 \frac{C_H}{C_L} - R_H^2 \right) n_H \right. \\ &\quad \left. + \left( \frac{C_H}{C_L} + N_L^* \right) R_L^2 \right) \end{aligned} \quad (5)$$

$$= \pi(-\alpha_1 n_H + \alpha_2) \quad (6)$$

where  $R_H$  and  $R_L$  is the sensing range radius of  $H$  and  $L$ , and  $\alpha_1 (= R_L^2 \frac{C_H}{C_L} - R_H^2)$  and  $\alpha_2 (= \frac{C_H}{C_L} + N_L^*) R_L^2$  are constants that are introduced for ease of notation.  $\alpha_1$  determines the impact of number of  $H$  devices on  $S_{tot}$ . Hence, as  $n_H$  increases, total sensing coverage ( $S_{tot}$ ) is determined as

$$S_{tot} \begin{cases} \text{decreases, if } C_H/C_L > (R_H/R_L)^2 \\ \text{stands, if } C_H/C_L = (R_H/R_L)^2 \\ \text{increases, if } C_H/C_L < (R_H/R_L)^2 \end{cases} \quad (7)$$

In this paper, we only consider the case for  $C_H/C_L > (R_H/R_L)^2$  ( $\alpha_1 > 0$ ) where total sensing coverage decreases as  $n_H$  increases, since, if  $\alpha_1 < 0$ , then it is desirable to replace all type  $L$  sensors with type  $H$  sensors in order to increase  $S_{tot}$ .

*Lifetime sensing coverage information* ( $S_{life}$ ) is defined as the sum of total sensing coverage information throughout network lifetime. The total network lifetime sensing information with  $n_H$  sinks is expressed as

$$S_{life}(n_H, T_d) = \sum_{t=0}^{T_d} S_{tot}(n_H, t) \quad (8)$$

where  $T_d$  is network lifetime and  $S_{tot}(n_H, t)$  is the total sensing coverage information at discrete time  $t$ , which indicates the sampling and gathering round for all functioning sensors in the field. Each sensor is assumed to collect the information from its sensing coverage and transmit it to the closest sink (high-cost sensor) at each round.

### C. Energy Consumption Model

Energy consumption model determines a device lifetime by considering application specific event characteristics, and network specific data extraction model and communication method. Basically, energy consumption for a single round is expressed as

$$E_{round} = E_D + E_S + E_T + E_R$$

where  $E_D$ ,  $E_S$ ,  $E_T$ , and  $E_R$  are the energies required for data processing, sensing, transmitting, and receiving per round time, respectively. The amount of energy spent in each operation would depend on the network and event model.

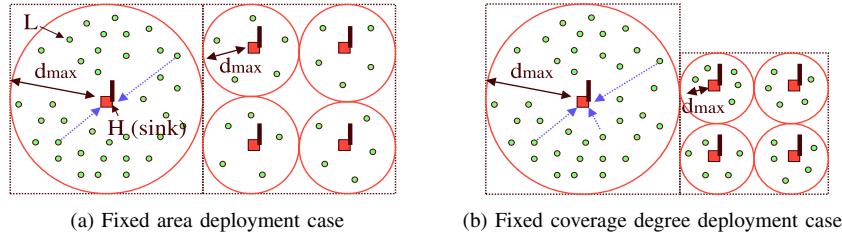


Fig. 1. Illustration of a heterogeneous deployment with single-hop direct communication mode for analysis. One sink and four sinks deployments are shown for both fixed area and fixed coverage degree case. In case of fixed area deployment, as  $n_H$  increases, coverage degree (node density) decreases. In case of fixed coverage degree deployment with the same node density, covered network area decreases as  $n_H$  increases.

1) *Communication model:* Two communication models are discussed in this paper: single-hop direct communication and multi-hop communication. In case of single-hop direct communication, each node can adjust the radio range to transmit data directly to the sink that is nearest to its own location. The per round energy consumption of  $L$  device that is a distance  $d$  from the nearest sink is

$$E_{round}(d) = E_1 + E_2 d^2 \quad (9)$$

where  $E_1$  consists of the energy required for data processing ( $E_D$ ), sensing ( $E_S$ ) and communication (radio electronics) that are independent of the node's radio range to the sink,  $E_2$  is the amplifier energy that is related to the distance from the sink, and the path-loss exponent is assumed to be 2. The energy operation ratio ( $E_2/E_1$ ) would be determined by the application.

In the multi-hop communication model, the energy consumption rate of each node mainly depends on the number of packets that are received and transmitted by the node. Periodic data gathering communication toward sink through a tree structure is assumed for our multi-hop heterogeneous deployment case. Thus,  $E_D$ ,  $E_R$  and  $E_T$  would be determined by the number of packets and the degree of data aggregation done by the intermediate node on the path towards the sink. While the distance from the sink is key factor in the energy consumption for a single-hop direct communication, the hop distance from the sink and the number of children on a data gathering tree determine the amount of packets handled and, accordingly, the energy consumption rate, in the multi-hop communication model.

2) *Application and event model:* Information and event characteristics depend on the sensor network application, and determine the amount of data processing in a node and the degree of data aggregation inside the network. Based on these characteristics, we may predict the temporal and spatial distribution of energy consumption rate for data sampling and processing of sensors in the network. This paper examines the case where the events are uniformly distributed across the network and periodic data gathering from all functioning sensors is performed each round, which results in the uniform energy consumption for data processing and sensing operations among nodes.

#### IV. ANALYSIS OF LIFETIME SENSING COVERAGE INFORMATION IN HETEROGENEOUS NETWORK

In this section, we evaluate lifetime sensing information extraction and coverage aging process with different mixture of heterogeneity in single-hop direct communication model. Lifetime sensing coverage is examined in two network deployment cases: fixed network area and fixed coverage degree. Fig. 1 shows two deployment environments. In our analysis, the initial deployed network area is assumed to consist of complete circles with one sink at the center of each circle, and  $L$  sensors are assumed to be equally distributed and uniformly deployed in each circle. This assumption is adopted to enable the problem tractable and the analysis results would hold for any single-hop heterogeneous deployments with uniformly distributed sensors, which are equally divided by the number of high-cost devices. In the first case (Fig. 1 (a)), the targeting network area ( $S_a$ ) to cover is fixed regardless of the number of sinks to be deployed. Thus, as the number of sinks increases, node density becomes sparser, which decreases the coverage degree, since  $S_{tot}$  decreases as  $n_H$  increases following (6). On the other hand, in the fixed coverage degree case (Fig. 1 (b)), the node density remains the same as the number of sinks increase, while covered network area decreases. This deployment condition affects the energy consumption rate since the the distance from the sink in each deployment is different as the number of sinks increases.

##### A. Lifetime Sensing Coverage with Fixed Network Area

In the analysis for the fixed network area ( $S_a$ ) with the single-hop direct communication model, the sensing coverage degree ( $S_d$ ) determines the coverage performance.

$$S_d(n_H) = S_{tot}(n_H)/S_a \quad (10)$$

1) *Network lifetime:* In the single-hop communication, a node that is furthest distant from a sink dies first according to (9). Thus, we represent network lifetime as  $T_d(d_{max})$ , which indicates the lifetime of a node that is  $d_{max}$ , (i.e., the maximum distance from the nearest sink), distant from a sink.  $d_{max}$  can be calculated as

$$d_{max}(n_H) = \sqrt{\frac{S_a}{\pi n_H}} \quad (11)$$

From (9) and (11), the lifetime of the node that has the maximum distance from the sink is calculated as

$$T_d(d_{max}(n_H)) = \frac{E_L}{E_{round}(d_{max}(n_H))} = \frac{E_L}{E_1 + E_2 d_{max}^2(n_H)} \quad (12)$$

$$= \frac{\pi E_L n_H}{\pi E_1 n_H + S_a E_2} \quad (13)$$

where  $E_L$  is the initial battery energy of type  $L$  sensor.

2) *Maximum lifetime sensing coverage:* From (8) and (13), the total sensing coverage information with  $n_H$  sinks till the first node depletes its battery energy can be expressed as

$$S_{life}(n_H) = \sum_{t=0}^{T_d(d_{max}(n_H))} S_{tot}(n_H, t) = \pi(-\alpha_1 n_H + \alpha_2) \frac{\pi E_L n_H}{\pi E_1 n_H + S_a E_2} \quad (14)$$

We can obtain the optimum number of sinks ( $n_{H-opt}$ ) that maximizes the total lifetime sensing coverage information by setting the derivative of (14) with respect to  $n_H$  to zero.

$$n_{H-opt} = \frac{1}{\sqrt{\alpha_1}} \sqrt{\left(\frac{S_a E_2}{\pi E_1}\right)^2 + \alpha_2 \frac{S_a E_2}{\pi E_1} - \frac{S_a E_2}{\pi E_1}}$$

From (5), we can evaluate the optimum number of sinks with respect to the cost ratio ( $C_H/C_L$ ), the initial number of sensors ( $N_L^*$ ), the sensing range ( $R_H, R_L$ ), and the ratio of energy consumption operations ( $E_2/E_1$ ) as

$$n_{H-opt} = \sqrt{\frac{\left(\frac{S_a E_2}{\pi E_1}\right)^2 + (R_H^2 + N_L^* R_L^2) \frac{S_a E_2}{\pi E_1}}{\frac{C_H}{C_L} R_L^2 - R_H^2}} + \frac{S_a E_2}{\pi E_1} - \frac{S_a E_2}{\pi E_1} \quad (15)$$

3) *Coverage Aging:* In the single-hop direct communication model, the nodes that have longer distance from the sink die faster. Before the first node dies, the coverage area ( $S_a$ ) remains the same as the initial size of deployment. After nodes begin to die, the coverage area decreases over time while the initial coverage degree ( $S_d$ ) is preserved throughout the remaining covered area. From (12), we can derive the coverage area aging function in the single-hop direct communication as

$$S_a(n_H, t) = \begin{cases} S_a, & \text{if } t < T_d(d_{max}(n_H)), \\ \frac{n_H \pi}{E_2} \left( \frac{E_L}{t} - E_1 \right), & \text{if } T_d(d_{max}(n_H)) \leq t \leq T_d(d=0). \end{cases} \quad (16)$$

The total sensing coverage  $S_{tot}(n_H, t)$  ages over time proportional to  $S_a(n_H, t)$ . We discuss the results of these expressions in Section IV-C.

### B. Lifetime Sensing Coverage with Fixed Coverage Degree

In the heterogeneous deployment with the fixed coverage degree ( $S_d$ ), the initial sensing coverage area changes depending on  $n_H$  while the node density remains the same. Since the

total network area varies with  $n_H$ , the impact of  $n_H$  on the network lifetime is more significant than the case of the fixed area deployment in Section IV-A, due to the different energy consumption rate.

$$S_a(n_H) = S_{tot}(n_H)/S_d \quad (17)$$

1) *Network lifetime:* We derive the network lifetime  $T_d(d_{max})$  following the fixed area case in Section IV-A.1.

$$d_{max}(n_H) = \sqrt{\frac{S_a(n_H)}{\pi n_H}} \quad (18)$$

We can derive  $S_a(n_H)$  from (6) and (17). From (12) and (18), the lifetime of the node with the maximum distance from the sink is calculated as

$$T_d(d_{max}(n_H)) = \frac{S_d E_L n_H}{(S_d E_1 - \alpha_1 E_2) n_H + \alpha_2 E_2} \quad (19)$$

2) *Maximum lifetime sensing coverage:* Lifetime sensing coverage information can be expressed from (8) and (19) as

$$S_{life}(n_H) = \frac{\pi(-\alpha_1 n_H + \alpha_2) S_d E_L n_H}{(S_d E_1 - \alpha_1 E_2) n_H + \alpha_2 E_2} \quad (20)$$

The optimum number of sinks ( $n_{H-opt}$ ) that maximizes the total lifetime sensing coverage information can be calculated by setting the derivative of (20) with respect to  $n_H$  to zero.

$$n_{H-opt} = \alpha_2 \left( \frac{\frac{E_2}{E_1} - \sqrt{\frac{S_d}{\alpha_1} \left( \frac{E_2}{E_1} \right)}}{\alpha_1 \frac{E_2}{E_1} - S_d} \right)$$

From (5), we have

$$n_{H-opt} = \left( \frac{C_H}{C_L} + N_L^* \right) R_L^2 \left( \frac{\frac{E_2}{E_1} - \sqrt{\frac{\frac{E_2}{E_1} S_d}{\left( \frac{C_H}{C_L} R_L^2 - R_H^2 \right)}}}{\left( \frac{C_H}{C_L} R_L^2 - R_H^2 \right) \frac{E_2}{E_1} - S_d} \right) \quad (21)$$

3) *Coverage Aging:* Coverage aging analysis with fixed coverage degree follows (16) except that  $S_a$  is replaced with  $S_a(n_H)$  when the time is less than  $T_d(d_{max}(n_H))$ . In addition, since  $T_d(d_{max}(n_H))$  has the larger gap with respect to  $n_H$ , the impact of heterogeneous deployment on coverage aging is more significant than that of the fixed area case.

### C. Discussion

In this section, we discuss the optimal heterogeneous deployment and diverse factors that affect the lifetime coverage with different mixture of heterogeneous.

1) *Impact of device cost and sensing range:* Fig. 2 shows how cost ratio and sensing range ratio of heterogeneous devices can affect the optimal heterogeneous deployment presented in (15) and (21). The parameter setting of these examples are following:  $N_L^* = 500$ ,  $E_2/E_1 = 0.2$ , and  $R_L = 0.1$ . For the fixed area deployment,  $S_a = 3\pi$ , and for the fixed degree deployment,  $S_d = 1$ . As discussed with (5) and (7) in Section III-B, as  $\alpha_1$  approaches to zero from positive value,

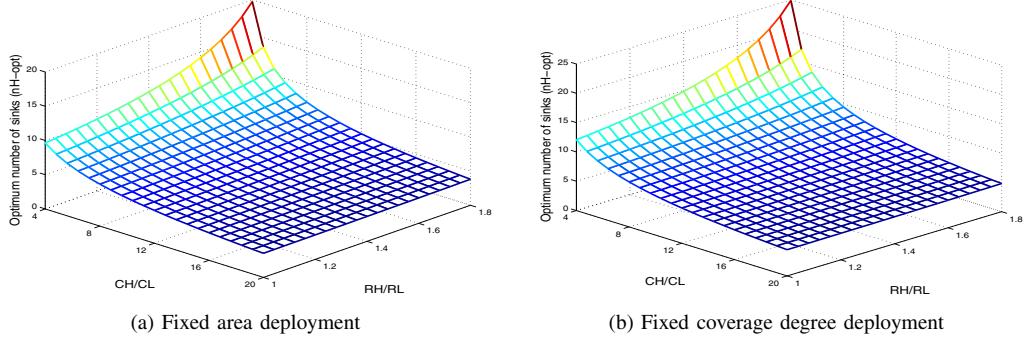


Fig. 2. Optimum number of sinks with respect to cost ratio ( $C_H/C_L$ ) and sensing range ratio ( $R_H/R_L$ )

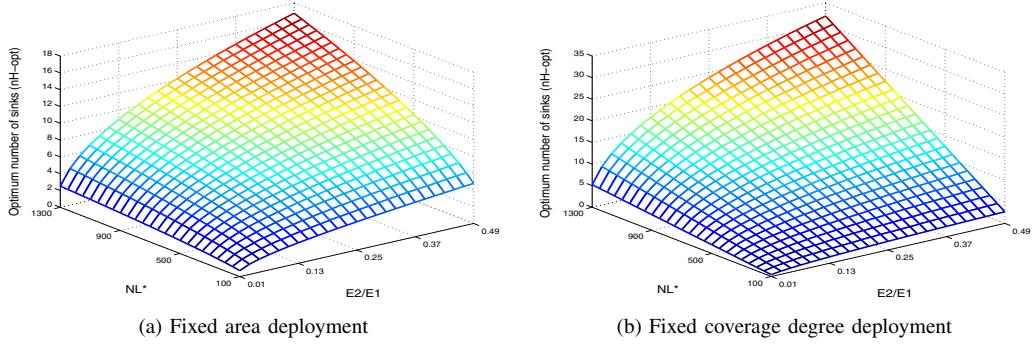


Fig. 3. Optimum number of sinks with respect to  $N_L^*$  and  $E_2/E_1$  ratio

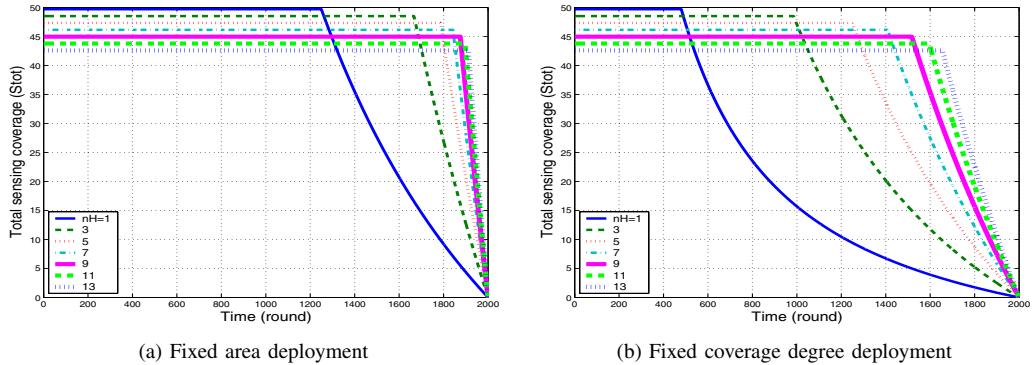


Fig. 4. Total sensing coverage ( $S_{tot}$ ) aging over time with respect to the number of sinks

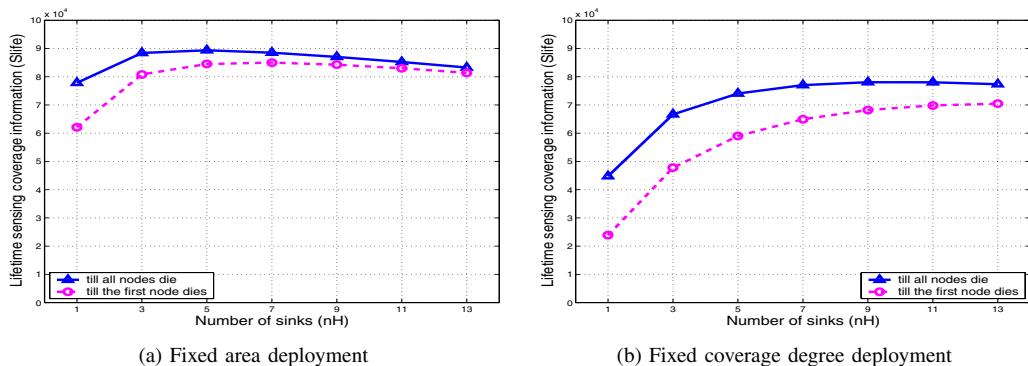


Fig. 5. Lifetime sensing coverage information ( $S_{life}$ ) with respect to the number of sinks. Two lifetimes are used: time to all nodes' death and time to the first node's death

i.e.,  $C_H/C_L$  approaches to  $(R_H/R_L)^2$ ,  $n_{H-opt}$  sharply rises. This is because that decreasing rate of  $S_{tot}$  with respect to  $n_H$  approaches to zero while  $T_d(d_{max})$  increases. Hence, as cost ratio decreases and sensing range ratio increases, it is desirable to deploy more number of  $H$  devices in order to increase lifetime sensing coverage. However, unless  $(R_H/R_L)^2$  is close to  $C_H/C_L$ , sensing range ratio does not affect heterogeneous deployments much as shown in this figure. Finally, the impact of cost ratio and sensing range ratio on  $n_{H-opt}$  are similar in both the fixed area and the fixed degree deployment, but the scale of  $n_{H-opt}$  is different.

2) *Impact of total cost and network operation:* Fig. 3 shows the impact of  $N_L^*$  and energy ratio ( $E_2/E_1$ ) in heterogeneous deployments. We use the following parameters for this figure.  $C_H/C_L = 10$ ,  $R_H = 0.2$  and  $R_L = 0.1$ .  $S_a = 3\pi$  for the fixed area deployment and  $S_d = 1$  for the fixed degree deployment. In case of the fixed degree deployment, the optimal  $n_H$  linearly increases with respect to  $N_L^*$ . The impact of  $N_L^*$  on optimal heterogeneous deployments is more significant in the fixed degree case than in the fixed area case, which is also indicated by the difference of z-axis scales between two figures. In addition, as the  $E_2$  portion increases, more  $n_H$  deployment is desirable to enhance the duration of network operation.

3) *Total sensing coverage aging:* Fig. 4 shows the aging process of total sensing coverage ( $S_{tot}$ ) throughout network with heterogeneous deployments. For this figure, we set  $C_H/C_L = 10$ ,  $N_L^* = 500$ ,  $E_L = 2000$ ,  $E_2/E_1 = 0.2$ ,  $R_H = 0.2$  and  $R_L = 0.1$ . For the fixed area deployment,  $S_a = 3\pi$ , and for the fixed degree deployment,  $S_d = 1$ . Since we only consider the positive  $\alpha_1$  as discussed in Section III-B, network with more  $n_H$  has the smaller total sensing coverage before aging starts. However, the increase of  $n_H$  enhances the duration of sensing operation while maintaining the initial coverage degree. Since the coverage degree in the remaining covered area is preserved uniformly over time,  $S_a$  aging follows the  $S_{tot}$ . As discussed in Section IV-B.3, compared to the fixed area deployment, the coverage aging initiation time ( $T_d(d_{max})$ ) is quite different among different mixtures of heterogeneous deployments in the fixed degree case. Thus, more  $n_H$  deployment is preferable in the fixed degree case than in the fixed area case as shown in Fig. 2 and Fig. 3.

4) *Lifetime sensing coverage:* Fig. 5 presents the lifetime sensing coverage information ( $S_{life}$ ) with respect to  $n_H$ . The parameters setting is the same as that of Fig. 4. We compare two lifetimes in this figure in order to observe the coverage aging effect. Since aging starts earlier with smaller  $n_H$ , larger difference between two lifetimes can be observed in smaller  $n_H$ . Compared to the fixed area deployment case, more  $n_H$  deployment achieves significant increase of lifetime sensing coverage in the fixed degree deployment. In addition, it is observed that the impact of heterogeneous deployments saturates as  $n_H$  increases. This is because that the decrease of initial total sensing coverage, as  $n_H$  increases, diminishes the advantage of network duration enhancement.

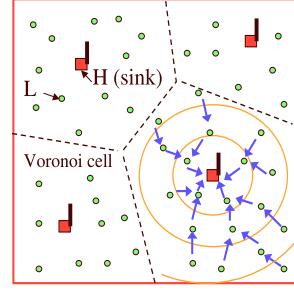


Fig. 6. Illustration of the multi-hop network model with  $n_H = 4$  for simulation

## V. SENSING COVERAGE AGING IN MULTI-HOP HETEROGENEOUS NETWORK

In this section, we present the simulation results of the lifetime sensing coverage and sensing coverage aging in multi-hop communication network for periodic data gathering applications. From the simulation results, the effect of increasing number of high-cost devices on lifetime coverage and aging behavior are examined with and without data aggregation.

In multi-hop heterogeneous network, all nodes participate in constructing the data gathering trees rooted at the nearest high-cost device ( $H$ ), which is functioning as a sink, as illustrated in Fig. 6. Thus, data gathering trees are formed such that all deployed sensor nodes are connected to a sink. Each node has a parent node that provides the forwarding path to the sink. A node receives data only from its children and forwards data only to its parent for data gathering purpose. In this simulation, all functioning and connected nodes process the sampling information from their own sensing coverage and forward the data to their sink for data gathering purpose at each round. Two extreme data aggregation modes (without aggregation and with perfect aggregation) are used for the simulation. In the case without data aggregation during data forwarding, all the packets from descendants are transmitted toward the sink without any modification or reduction of the data size. When perfect data aggregation is performed, we assume that all the data from the children of a node at each round can be aggregated into one data packet with its own data (e.g., MIN, MAX, SUM, COUNT).

For the simulation, we deploy 200 nodes for  $N_L^*$  and set 10 for  $C_H/C_L$ . Three sensing range ratios ( $R_H/R_L = 1, 1.5, 2$ ) of high-cost device to low cost device are performed. As  $n_H$  increases,  $n_L$  is calculated by (3). Sensing range of the low-cost device  $L$  is set to the half size of its radio range.  $H$  and  $L$  nodes are uniformly and randomly placed in the unit square area. 30 different random deployments for each  $n_H$ ,  $R_H/R_L$  ratio, and with/without data aggregation cases are performed and averaged for each simulation results. In order to monitor the coverage area and the coverage degree by randomly deployed sensors over time, 400 grid points (20 by 20) are placed in this unit square area, which allows one low-cost sensor covers around 7 grid points in average. The nearest node in the upper hop level toward the sink is selected for the parent of each node, which follows the data gathering

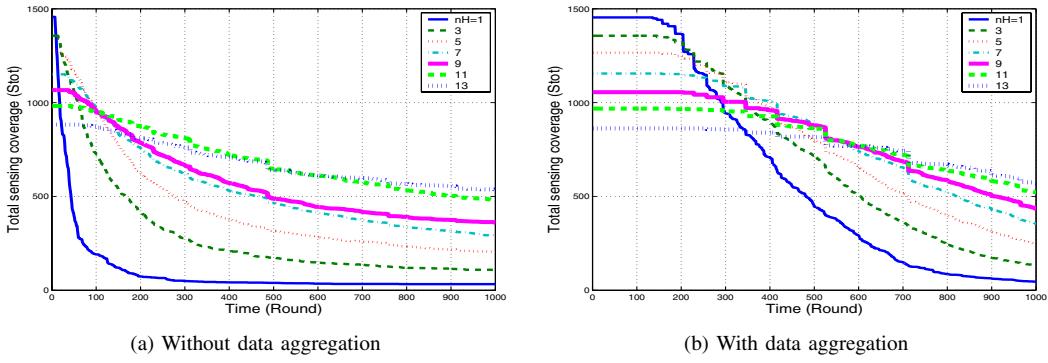


Fig. 7. Total sensing coverage ( $S_{tot}$ ) aging over time with respect to the number of sinks ( $n_H$ )

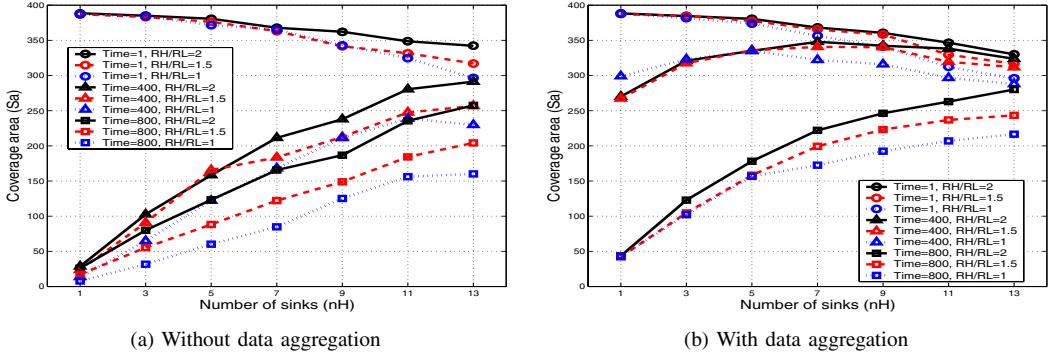


Fig. 8. Sensing coverage area ( $S_a$ ) aging over time with respect to the number of sinks ( $n_H$ )

construction method in [13]. Nodes search for a new parent when the current parent dies or becomes disconnected from the data gathering tree. If the node fails to find a new parent, then the node gets disconnected from the tree and is regarded as a non-functioning node even though the sufficient energy still remains.

#### A. Total Sensing Coverage Aging

In Fig. 7, we examine total sensing coverage ( $S_{tot}$ ) aging over time with respect to the number of sinks without and with perfect data aggregation case when  $R_H/R_L = 2$ . Both cases show that smaller  $n_H$  provides higher total sensing coverage in the beginning stage of network lifetime. As nodes become energy-depleted, coverage starts to degrade over time. Smaller  $n_H$  achieves higher initial total sensing coverage since the larger number of  $n_L$  is available under total cost constraints. However, in case of network without data aggregation in Fig. 7 (a), the homogeneous deployment with one sink shows drastic decrease of coverage in quite early stage as compared to the multiple sinks deployment. This drastic decrease of sensing coverage is mainly due to the first hop nodes death and the consequent connectivity loss of nodes in the further hop levels. Since the fewer sinks should handle more number of  $L$  sensors, the energy consumption rate of the first hop is much higher compared to that with larger  $n_H$  deployments. As  $n_H$  increases, network maintains the initial coverage for longer time.

When data aggregation is available as shown in Fig. 7 (b), the initial coverage is preserved much longer period

as compared to the case without data aggregation. If all nodes can perform perfect data aggregation, the number of packets transmitted to a sink can be drastically reduced, which enhances the network lifetime much longer. In addition, except one sink deployment, multiple sinks deployments show similar total sensing coverage and aging pattern from the middle of network lifetime.

#### B. Sensing Coverage Area Aging

Total sensing coverage in Fig. 7 implies both coverage area and coverage degree. Thus, we show coverage area aging and degree aging in Fig. 8 and Fig. 9 respectively. In Fig. 8, the initial coverage areas with respect to  $n_H$  show similar since we randomly deploy sensors in a fixed size of area regardless of  $n_H$ . Thus, the initial coverage difference exists in sensing coverage degree. The coverage area aging without data aggregation in Fig. 8 (a) shows the significant reduction in smaller  $n_H$  deployments. When time=400 and 800, as  $n_H$  increases the preserved coverage area increases almost linearly.

In contrast, in the network with perfect data aggregation case in Fig. 8 (b), deploying more number of sinks beyond a certain point does not show higher coverage area when time=400. Even at time=800, the coverage area saturates as  $n_H$  increases. This implies the energy depletion of nodes, especially the first hop nodes, which provide the connection to a sink, would be similar with respect to  $n_H$  compared to the case without data aggregation.

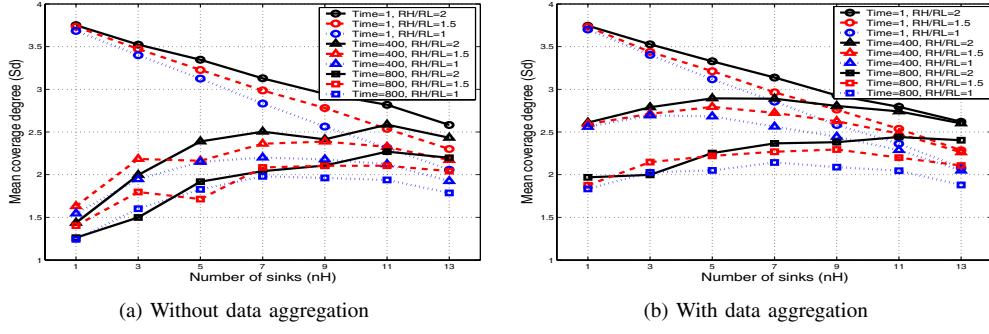


Fig. 9. Sensing coverage degree ( $S_d$ ) aging over time with respect to the number of sinks ( $n_H$ )

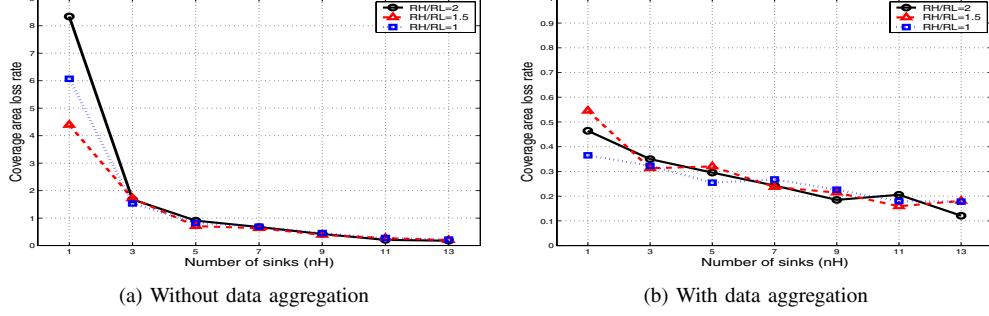


Fig. 10. Coverage area loss rate (points / round) given the number of sinks ( $n_H$ )

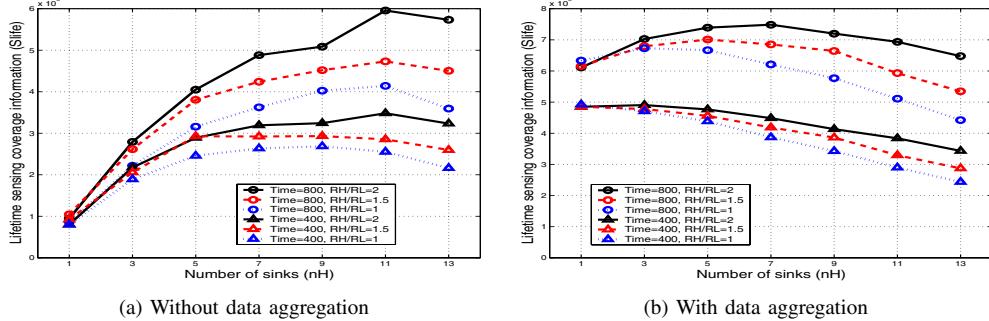


Fig. 11. Lifetime sensing coverage information ( $S_{life}$ ) with respect to the number of sinks ( $n_H$ )

### C. Sensing Coverage Degree Aging

Fig. 9 shows the average sensing coverage degree in covered area as nodes get energy depleted over time. Initial coverage degree decreases linearly as  $n_H$  increases since the smaller number of low-cost sensors are deployed in a fixed network area. Deployments with the smaller  $n_H$  shows the drastic decrease of the coverage degree over time in the covered area. It is observed that even though deployments with higher number of high-cost devices can maintain the larger coverage area over time, the coverage degree decreasing rate over time is much smaller.

### D. Coverage Area Loss Rate

Fig. 10 shows the coverage area loss rate with respect to the number of sinks, which indicates the number of grid points that becomes to lose coverage per round. Coverage area loss rate is calculated during the beginning stage of coverage area

aging from 1% to 20% of initial coverage area loss. It is observed that the coverage area loss rates among different sensing range ratios show little difference. In Fig. 10 (a), we observe the drastic difference of coverage loss rate between one sink deployment and the multiple sinks deployments. As the number of sinks increases, the difference of coverage loss rate decreases. Since the maximum hop distance is not much reduced as the number of sinks increases, the effect of more sinks deployments on the coverage aging becomes less significant.

In contrast, in the network with data aggregation, the coverage area loss rate is similar among different  $n_H$ . It should be noticed that the y-axis scale of Fig. 10 (b) is much finer than that of Fig. 10 (a). Since the amount of data communication is independent of the descendent of a node in case of perfect data aggregation, shorter hop distance resulted by more  $n_H$  deployment does not reduce as much energy consumption as that without data aggregation.

### E. Lifetime Sensing Coverage Information

Fig. 11 shows lifetime sensing coverage information ( $S_{life}$ ) throughout the network lifetime with respect to the number of sinks. It is observed that the effect of sensing range ratio becomes more significant as network ages, which is indicated by comparing  $S_{life}$  at time=400 and time=800. In Fig. 11 (a), the heterogeneous deployment with 11 sinks achieves about 6 times as much lifetime sensing coverage as the homogeneous deployment with one sink can obtain till time=800. Beyond that point, the increase of  $n_H$  does not gain more lifetime sensing coverage since the initial coverage becomes smaller.

In contrast, as illustrated in Fig. 11 (b), the lifetime sensing coverage with data aggregation decreases as  $n_H$  increases when time=400. Since smaller initial coverage (especially the coverage degree) offsets the increase of duration of network coverage in heterogeneous deployments as discussed in Section V-D, the gain of increasing  $n_H$  is little for the network with perfect data aggregation.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we examined the impact of heterogeneous device deployment on lifetime sensing coverage and coverage aging process with mathematically and through simulation.

First, we identified the trade-offs in deploying high-cost devices under total cost constraints. High-cost devices can function as a cluster-head or sink to collect and process the data from low-cost sensors, which can enhance the duration of network sensing operation. However, the higher cost of these devices can reduce the number of low-cost sensors, which leads to the decrease of the initial sensing coverage: either in terms of coverage area or coverage degree. An optimal heterogeneous deployment can achieve lifetime sensing coverage by several times as much as that with homogeneous deployment considering both initial coverage and the duration of sensing operation.

Second, we presented the expression to find the optimum number of high-cost devices in the single-hop communication model that maximizes the lifetime sensing coverage information incorporating several factors that affect the initial sensing coverage and the energy consumption of nodes. Regarding sensing range ratio, unless  $(R_H/R_L)^2$  is close to  $C_H/C_L$ , it does not affect coverage much.

Finally, the coverage aging patterns with two communication models and different ratio of heterogeneity have been examined. In the single-hop communication model, initial coverage degree can be preserved in the covered area as nodes get energy-depleted over time since the communication energy consumption is dependent on not neighboring nodes, but the distance from the sink. In the multi-hop communication model, coverage degree aging is observed because energy consumption is highly affected by the number of children as well as the hop distance. In addition, connectivity is the necessary factor that maintain the coverage. We observed that the deployment with smaller  $n_H$  shows the drastic decrease of, not only the coverage area, but also the coverage degree in the remaining covered area over time. Regarding the coverage aging rate, as

$n_H$  increases, faster aging in the single-hop communication and slower aging in the multi-hop communication is observed. From the perspective of re-deployment, uniform faster aging rate would be preferred since the re-deployment can be done at once for the entire area. However, the fast coverage aging with smaller  $n_H$  in the multi-hop case is not due to the energy depletion of overall nodes, but due to the connectivity loss caused by the early energy depletion of the first-hop nodes while the majority of nodes still have enough energy to perform sensing operation in the field.

In this paper, we have focused on the heterogeneous deployments with two different communication models in a network where periodic data gathering is performed with uniform event distribution. Other network operations, applications, event models and energy saving schemes with practical settings can be considered in the deployment problem of heterogeneity and analysis of network aging process. In addition, network aging affects network reliability, load-balancing and re-deployment decision. As for sensing coverage, the different application and event characteristics would demand different requirements. We plan to extend the current work to the above directions in the future.

## ACKNOWLEDGMENT

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