# Coverage Issue in Sensor Networks with Adjustable Ranges [*]

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## Abstract

*In this paper, we study the problem of maintaining sensing coverage by keeping a small number of active sensor nodes and a small amount of energy consumption in wireless sensor networks. This paper extends a result from [21] where only uniform sensing range among all sensors is used. We adopt an approach that allows non-uniform sensing ranges for different sensors. As opposed to the uniform sensing range node scheduling model in [21], two new energy-efficient models of different sensing ranges are proposed. Our objective is to minimize the overlapped sensing area of sensor nodes, thus to reduce the overall energy consumption by sensing to prolong the whole network's life time, and at the same time to achieve the high ratio of coverage. Extensive simulation is conducted to verify the effectiveness of our node scheduling models.*

## 1 Introduction

Recent improvements in affordable and efficient integrated electronic devices have had a considerable impact on advancing the state of wireless sensor networks [1, 6, 10], which constitute the platform of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring. An important problem receiving increased consideration recently is the *sensor coverage problem*, centered around a fundamental question: *How well do the sensors observe the physical space?* In some ways, it's one of the measurements of the QoS of sensor networks. The coverage concept is subject to a wide range of interpretations due to a variety of sensors and applications. Different coverage formulations have been proposed, based on the subject to be covered (area versus discrete points) [11, 12], the sensor deployment mechanism (random versus deterministic), as well as other wireless sensor network properties (e.g. network connectivity and minimum energy consumption).

Another consideration is that the energy of sensor networks is scarce, and it is always inconvenient or even impossible to replenish the power. One solution is to leverage redundancy of deployment to save power, for in most cases, the density of sensor nodes is much higher than needed [13]. Node scheduling or density control is used to achieve this goal. A set of active working nodes is selected to work in a round and another random set in another round, meanwhile a high degree of coverage is maintained. All the other non-selected nodes are turned off into the sleeping mode which needs very little energy. In this way, the overall consumed energy of the sensor network can be saved and the lifetime prolonged.

In this paper, we focus on area coverage with random sensor deployment. The basic goal is to activate a subset of sensors in a densely deployed environment subject to one global constraint – coverage. Two conflicting objectives are, (a) minimizing the number of active sensors to minimize the energy consumption and (b) maintaining the coverage. We propose two novel node scheduling models with adjustable sensing ranges, opposed to the traditional uniform sensing range node scheduling method. That is, the working nodes selected in one round could have several-level adjustable sensing ranges, and each one chooses to have one range based on its relative location according to the model used. By adopting smaller granularity, the overlapped area and hence the sensing energy consumed are reduced. A high degree of coverage can still be provided.

The rest of the paper is organized as follows. In section II, we will give a brief summary of the related work. In section III, we introduce our two node scheduling models and present the theoretical analysis about the energy consumption of these

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models. In section IV, we will give the simulation and evaluation results. Section V is the conclusion remarks and our future work.

## 2 Related work

A key issue of the wireless sensor network is the coverage problem, and in most cases, "coverage" means area coverage. It can be viewed as one of the measurements of *quality of service* of the system. When the ratio of coverage falls below some predefined value, the sensor network can no longer function normally. Most sensor networks have the characteristics of high node density and limited node power. The goal is to minimize energy consumption to prolong the system lifetime while maintaining coverage. Coverage can be achieved by designing some kind of density control mechanism, that is, scheduling the sensors to work alternatively to minimize the waste of sensing power due to the overlap of sensor nodes' sensing area.

In [14], Slijepcevic *et al.* proved the problem of finding maximal number of covers in a sensor network to be NP-complete, where a cover is a set of nodes that can completely cover the whole monitored area. Several approximate methods are developed to solve this problem.

Xu *et al.* in [17] introduced GAF. This method divides the monitored area into rectangular grids and selects a leader in each grid to be the working node. The maximum distance between any pair of working nodes in adjacent grids is within the transmission range of each other. This method can ensure connectivity, but not complete coverage, the 100% coverage of the monitored area. Ye *et al.* in [19], [20] developed a distributed density control algorithm named PEAS, which is probing based. This algorithm also divides the area into grids, and assumes that each grid has at least one sensor. In PEAS, a sleeping node wakes up and broadcasts a probing message within a certain range after its sleeping period; if no reply is received after a timeout, it will turn on to work until it depletes its energy. The probing range can be adjusted to achieve different levels of coverage overlap, but it can not guarantee complete coverage, either.

In [15], Tian *et al.* developed a sponsored area algorithm which aims at providing complete coverage by its off-duty eligibility rules. A node can turn itself off as long as its working neighbors can cover all of its sensing area. This rule underestimates the area already covered, therefore much excess energy is consumed. In [21], this algorithm is proved to be inefficient. Zhang and Hou's work [21] is of much importance. They also aim at complete coverage. They at first proved an intuitive but fundamental result, i.e., if the transmission range $r_t$ is at least twice the sensing range $r_s$, a complete coverage of a convex area implies connectivity of the working nodes. It is the first work to investigate the relationship between coverage and connectivity. Based on this, they further introduced a distributed, localized density control algorithm named OGDC. In the ideal case, when all the nodes have the same sensing range and transmission range, every three closest nodes in a cover can form an equilateral triangle with the side length $\sqrt{3}r_s$. Thus the overlap of sensing areas of all the nodes is minimized. The working nodes can be activated by a starting node which is randomly generated in a progressively spreading way. Simulation results show that OGDC has better performance than other algorithms in both coverage and energy consumption aspects.

In [18], Yan *et al.* proposed an adaptable sensing coverage mechanism which could provide differentiated surveillance service. In that protocol, nodes could dynamically decide their own working schedule to provide not only complete coverage, but the degree of coverage $\alpha$. $\alpha$ could be less than 1 or larger than 1. If a monitored point needs the coverage 2, that means it needs to be covered by two sensors together all the time. This protocol achieves both energy efficiency and differentiated degree of sensing coverage. It aims at providing degree of coverage, but the current algorithm can not correctly guarantee with $\alpha > 2$. Other researchers have also done some work in this very field, such as [7], [8] and [16].

Additional kinds of coverage are point coverage and barrier coverage. In the point coverage problem, the objective is to cover a set of points. [2] and [4] are both methods for this problem, using random and deterministic deployment separately. The barrier coverage is coverage with the goal of minimizing the probability of undetected penetration through the barrier (sensor network) [5]. In [12], a model is proposed to find the maximal breach path (MBP) and maximal support path (MSP) of the agent. They correspond to the worst and best case coverage.

## 3 Adjustable Sensing Range Node Scheduling Model

To our best knowledge, most of the density control algorithms assume the sensing ranges of all the sensors to be identical. In [15], Tian *et al.* mentioned that nodes can have different sensing ranges due to initial set up or changes made during their lifetime. In our work, we will utilize the adjusta-

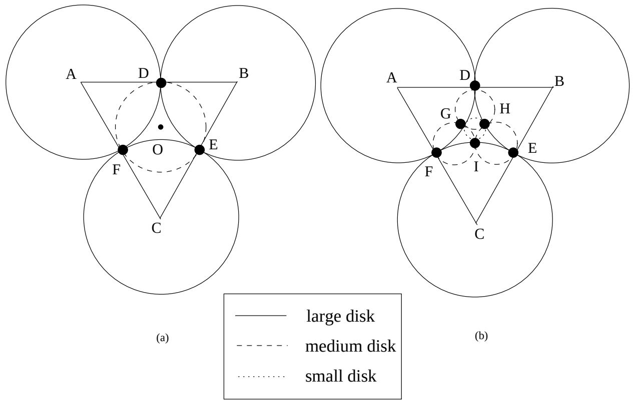


**Figure 1. (a) Coverage with two sensing ranges (Model II). (b) Coverage with three sensing ranges (Model III).**

bility of sensing range to design the node scheduling scheme to minimize the energy consumption as much as possible.

### 3.1 Assumptions

As mentioned above, we will deal with the randomly deployed sensor nodes. We assume the nodes to be static once deployed, and that each knows its own location. This can be achieved using some location system [3], [9]. In the following description, we will deploy the sensor network to a two-dimensional square area. The target area to be monitored will be smaller than the deployed one to eliminate the edge effect. The models proposed can be extended to three-dimensional space with little modification. The sensing range of a node is defined as a circle of radius $r_s$ centered at the location of this very node. In the following, we will denote the area covered by a node as its sensing disk.

Since the relationship of coverage and connectivity has been proved in [21], here we assume the transmission range of sensor nodes to be at least twice the sensing range. Coverage can imply connectivity, so the following discussion and simulation will deal only with the coverage problem.

### 3.2 Proposed Node Scheduling Models

In [21], Zhang and Hou proposed a node scheduling model using uniform sensing range. To minimize the number of working nodes for energy conserving purposes, the overlap of sensing disks of working nodes should be minimized. The model they put forward is that in the ideal case, the center points of the three closest nodes should form an equilateral triangle with side length $\sqrt{3}r_s$, where $r_s$ is the radius of the disks.

As opposed to this uniform sensing range model (we will denote it as Model I in the following discussion), we propose two other node scheduling models with several levels of adjustable sensing ranges. That is, we relax the condition of uniform sensing range to achieve better performance, i.e., less energy consumption per monitored area. One model (see Figure 1) utilizes two adjustable sensing ranges (large disks and medium disks, denoted as $r_{ls}$, $r_{ms}$); the other uses three adjustable sensing ranges (large disks, medium disks, and small disks, denoted as $r_{ls}$, $r'_{ms}$, and $r_{ss}$). The scheduling operates such that the whole lifetime of the sensor network is divided into rounds. In each round, a set of nodes is selected to do the sensing job with different sensing ranges according to the model used. In another round, another set will be turned on. This is done in a random way, so the energy consumption among all the sensors is balanced. We will put forward the detailed description of the models in the following. They are in the ideal case, that is to say, we assume that we can find a sensor at any desirable position.

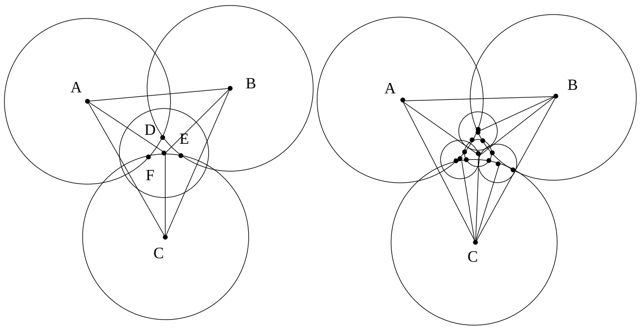
#### 3.2.1 Coverage with Two Adjustable Sensing Ranges (Model II)

This coverage approach uses two types of sensing ranges to cover all the area. The following describes how to place these sensing disks.

- Cover the area with non-overlapping large disks such that each disk “touches” six disks. The touching point is called a *crossing*.
- The area enclosed by three adjacent disks is not covered. Then, cover the area with a medium disk. That is, three crossings are on the circumference of the medium disk.

**Theorem** 1: *In coverage with two adjustable sensing ranges,* $r_{ms} = (1/\sqrt{3})r_{ls}$.

*Proof.* In Figure 1 (a) (Model II), the three sensor disks centered at $A$, $B$, $C$ with large sensing range $r_{ls}$ are tangent to one another with the tangential points $D$, $E$, $F$. The medium sensing disk should cover all the *crossing* nodes $D$, $E$, $F$, so the smallest one is the disk which has the three *crossings* on its circumference. Since disks are tangent, the crossing point $D$ is on line $AB$, and $E$ on $BC$, $F$ on $AC$, so the medium disk is inscribed to the equilateral triangle $\triangle ABC$. If we denote the center of the medium disk as $O$, we can calculate the diameter of medium disk $O$ to be $(1/\sqrt{3})r_{ls}$. $\square$



(a) (b)

**Figure 2. Transmission range calculation in real application case. (a) Model II. (b) Model III.**

In the ideal case, the transmission range of the large disk is twice its sensing range as described in the assumption above. In real application, to guarantee complete coverage, the distance between any two such nodes will be limited within $2r_{ls}$, (they are intersected or tangent). Therefore, the transmission range of $2r_{ls}$ can ensure connectivity. In this model, the node with a medium sensing disk will transmit the data to one of the nodes with large sensing disks; its transmission range is $(2/\sqrt{3})r_{ls}$. In real application, see Figure 2 (a), the three large disks are intersected or tangent, and the medium disk is expected to cover all the three *crossings*, $D$, $E$, $F$. So the distance between its center and one of the large nodes will be no more than $(2/\sqrt{3})r_{ls}$, which is its value in the ideal case.

### 3.2.2 Coverage with Three Adjustable Sensing Ranges (Model III)

This coverage approach uses three types of sensing ranges to ensure the coverage. The following describes how to place these sensing disks.

- Cover the area with non-overlapping large disks such that each disk "touches" six disks.
- The area enclosed by three adjacent disks is uncovered. Embed a small disk in the area so that it "touches" all three large disks. Three new uncovered areas are generated which are covered by three medium disks.

**Theorem** 2: *In coverage with three adjustable sensing ranges,* $r_{m's} = (2/\sqrt{3} - 1)r_{ls}$, $r_{ss} = (2 - \sqrt{3})r_{ls}$

*Proof.* In Figure 1 (b) (Model III), the large disks centered at $A$, $B$, $C$ are tangent. The small sensing disk centered at $O$ is the circumcircle of them all with tangential points $G$, $H$, $I$. Its diameter is $r_{ss} = (2 - \sqrt{3})r_{ls}$. The medium sensing disk is to cover the uncovered area enclosed by the four already existing large and small sensing disks. It should cover all the *crossings*. One should have the points $D$, $G$, $H$ on its circumference, the second should have $E$, $H$, $I$, the third $F$, $I$, $G$. They are tangent with lines $AB$, $BC$, $AC$ separately. The diameters of the medium disks are $(2/\sqrt{3} - 1)r_{ls}$. □

The transmission range of the large disks is the same as that of the large disks in Model II, twice its sensing range in both ideal case and real case to guarantee complete coverage. As in Figure 2 (b), the small sensing disk will be the circumcircle of the three large ones, or they are intersected if the ideal assumption can't be achieved in real case. The distance between the centers of the small one and one of the large ones is no more than $(2/\sqrt{3})r_{ls}$. If the node with small sensing disk transmits data to the node with medium sensing disk, its transmission range is at most $(1/\sqrt{3})r_{ls} - r'_{ms}$, the distance between these two nodes. The node with medium sensing disk will transmit its data to neither the node with small sensing disk or the large one. Its transmission range could be $(1/\sqrt{3})r_{ls} - r'_{ms}$ or $\sqrt{r_{ls}^2 + r_{m's}^2}$ according to different data gathering strategy. In real case, the value of its transmission range won't be larger than the one in the ideal case. In both Model II and Model III, the transmission range of large disk nodes is twice their sensing range ($2r_{ls}$); the transmission range of medium disk or small disk is less than the sum of its sensing range and the sensing range of a large disk node.

### 3.3 Energy Consumption Analysis

We consider only the energy consumed by the sensing function, do not include the transmission power and calculation power consumption, and take the consumed power as zero when the sensor node is sleeping. We assume that the power consumed by working sensor node to deal with sensing task in a round is proportional to $r_s^4$ or $r_s^2$, according to different energy consumption models. (In the following, we will use $r$ to indicate $r_{ls}$ for convenience.)

1. *Energy consumption of Model I, (Figure 3 (a)).* The efficient area $S_1$ covered by the

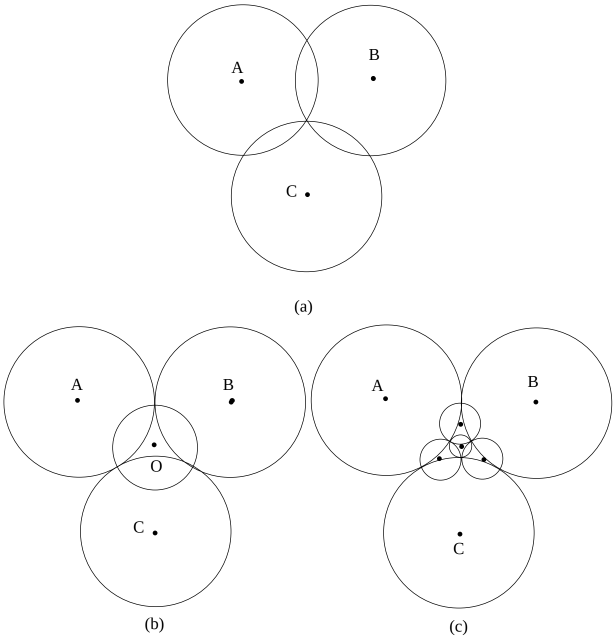


**Figure 3. Coverage calculation of three models. (a) Model I. (b) Model II. (c) Model III.**

three sensors is the area which could be monitored by at least one of the three sensor nodes, so the area of it is as shown in equation ( 1).

$$S_1 = (2\Pi + \frac{3\sqrt{3}}{2})r^2 \tag{1}$$

The total sensing energy consumption of these three sensors is proportional to $3r^2$ ($E$) or $3r^4$ ($E'$). So the energy consumption per area is as shown in equations ( 2) and ( 3), separately. Here the parameters $\mu_1$ and $\mu_2$ are power consumption per unit. We use ($Joule$ / $r^2$) and ($Joule$ / $r^4$) as their dimensions.

$$E_1 = \frac{3r^2\mu_1}{(2\Pi + \frac{3\sqrt{3}}{2})r^2} = 0.3379\mu_1 \tag{2}$$

$$E_1' = \frac{3r^4\mu_2}{(2\Pi + \frac{3\sqrt{3}}{2})r^2} = 0.3379r^2\mu_2 \tag{3}$$

2. *Energy consumption of Model II, (Figure 3 (b)).* In Model II, the efficient area $S_2$ covered by the four sensors can be calculated by the following equation ( 4).

   $$S_2 = (\sqrt{3} + \frac{5}{2}\Pi)r^2 \tag{4}$$

   By Theorem 1, we know the radius of the medium disk is $(\sqrt{3}/3)r$. The energy consumption per area is the ratio of the overall energy consumption of the three large sensing range nodes and one medium sensing range node to the efficient area covered by these nodes. Equation ( 5) and ( 6) are for different energy models.

   $$E_2 = \frac{(3r^2 + \frac{r^2}{3})\mu_1}{(\sqrt{3} + \frac{5}{2}\Pi)r^2} = 0.3479\mu_1 \tag{5}$$

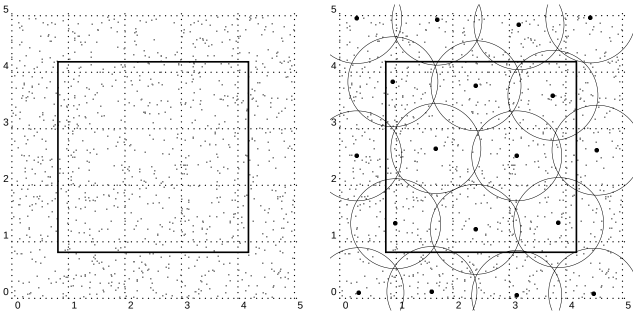
   $$E_2' = \frac{(3r^4 + \frac{r^4}{9})\mu_2}{(\sqrt{3} + \frac{5}{2}\Pi)r^2} = 0.3247r^2\mu_2 \tag{6}$$

3. *Energy consumption of Model III, (Figure 3 (c)).* In Model III, the efficient area $S_3$ covered by the seven sensors is equal to the one in Model II, so it can be calculated using equation ( 4). According to Theorem 2, the radius of the medium disk is $(2 - \sqrt{3})r$, and the radius of the small disk is $(2\sqrt{3}/3 - 1)r$. The energy consumption is shown in equation ( 7) and ( 8).

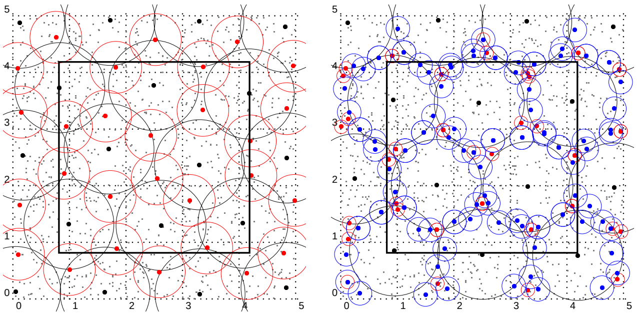
$$\begin{aligned} E_3 &= \frac{(3r^2 + 3(7 - 4\sqrt{3})r^2 + (\frac{7}{3} - \frac{4\sqrt{3}}{3})r^2)\mu_1}{(\sqrt{3} + \frac{5}{2}\Pi)r^2} \\ &= 0.3380\mu_1 \end{aligned} \tag{7}$$

$$\begin{aligned} E_3' &= \frac{(3r^4 + 3(97 - 56\sqrt{3})r^4 + (\frac{97}{7} - \frac{56\sqrt{3}}{9})r^4)\mu_2}{(\sqrt{3} + \frac{5}{2}\Pi)r^2} \\ &= 0.3148r^2\mu_2 \end{aligned} \tag{8}$$

By theoretical analysis, we can see that if the energy consumed by sensing is proportional to $r_s^4$, then both Model II and Model III will be more energy-efficient than Model I, and if it's proportional to $r_s^2$, then they won't have advantages. Generally, if we assume the energy consumption by sensing is $\mu r^x$, (proportional to $r^x$, where $x > 0$), then $E_1 = 0.3379r^{x-2}$, $E_2 = (3 + 0.577^x)/9.582$, and $E_3 = (3 + 0.1547^x + 0.268^x)/9.582$. Therefore, when $x > 2.26$, $E_2 < E_1$; $x > 1.38$, $E_3 < E_1$. We can have that when $x > 2.62$, both Model II and Model III will have less energy consumption than Model I.



(a) Randomly deployed nodes (b) Working nodes selected in Model I



(c) Working nodes selected in Model II (d) Working nodes selected in Model III

**Figure 4. 1000-node random network.**

# 4 Performance Evaluation and Simulation

## 4.1 Simulation Environment

In order to evaluate our proposed models, we compare them with Model I proposed by Zhang *et al.* Since in [21], the optimal geographical density control (OGDC) algorithm, which is based on Model I, has been proved to have better performance than PEAS algorithm [20], the hexagon-based GAF-like algorithm, and also the sponsored area algorithm [15], we do not include the evaluation of these algorithms in the following evaluation.

We customize a simulator to do the simulation. Since the issue we are to study is sensing coverage, some other issues such as mobility, MAC layer protocol and transmission are all ignored in our simulator. We set up our simulation in a $50 \times 50m^2$ network area. Sensor nodes are randomly distributed in the field initially and will remain stationary once deployed. To calculate sensing coverage, we divide the space into $500 \times 500$ unit grids, and if the center point of a grid is covered by some of a sensor node's sensing disk, we assume the whole grid to be covered. We will use the middle $(50 - r_s) \times (50 - r_s)m^2$ as the monitored target area to calculate the coverage ratio to ignore the edge effect, for in the real case the monitored area will be sufficiently larger than the sensor's sensing disk. We take the transmission range of the sensors being twice large sensing range as the assumption based on Theorem 1 proved in [21], which states that transmission range that is at least twice the sensing range is both necessary and sufficient to ensure that coverage implies connectivity. We concentrate only on the coverage and energy consumption issues in the simulation.

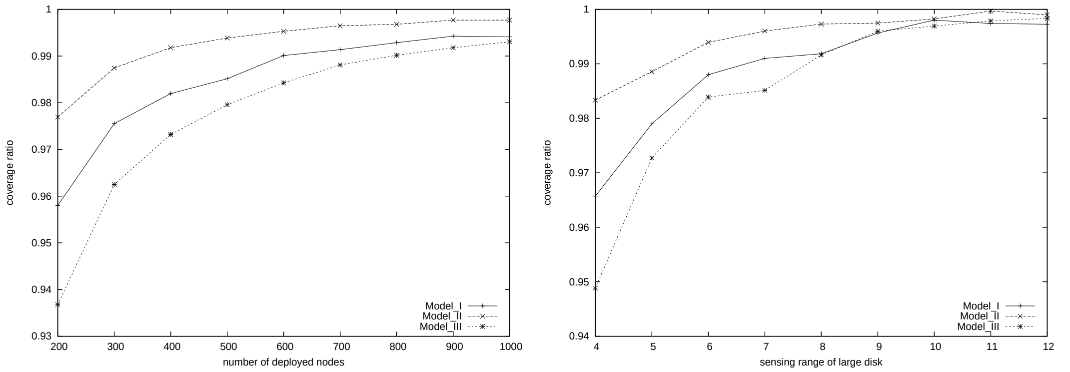
## 4.2 Parameters Used and Performance Metrics

In the simulation, we relax the assumption of ideal case and replace it with 'find the sensor node closest to the desirable position needed'. The overall coverage ratio will be less than 100% and will vary with the different values of the parameters used. The tunable parameters in our simulation are as follows. (1) The node density. We change the number of deployed nodes from 200 to 1000 to see the effect of node density on the models. (2) The sensing range. We change the sensing range of the sensor nodes who have the large sensing disk from $4m$ to $12m$. (The sensing range of the medium disk and small disk in Model II and Model III will change accordingly).

The performance metrics are: (1) The percentage of coverage, i.e., the ratio of the covered area to the total monitored area. We will use the $500 \times 500$ bit map to denote them. (2) Sensing energy consumed in one round. Here we assume the energy consumed by sensing is proportional to $r_s^4$.

## 4.3 Simulation Results

Figure 4 (a) shows the random deployment of 1000 sensor nodes in $50 \times 50m^2$ area in our simulation. (b) $\sim$ (d) are the working nodes selected in Model I, Model II and Model III with different sensing disks in a certain round. The sensing range of large disk nodes is $8m$. The boxes are to show the monitored target area. Figure 5 shows the coverage variation when the node density or node sensing range changes. (In (a), the sensing range is the one of large disk nodes.) We can see from this that with different node density and sensing range, Model II can achieve better coverage ratio than Model I and Model III, especially when node density is low or sensing range is small. Model III doesn't perform better than Model I. But when node density is high (close to ideal case), Model III can get similar coverage ratio as Model I. When sensing range is large enough, the three models will have very close performance in coverage. Figure 6 is the sensing energy consumption in one



(a) Coverage vs. number of deployed nodes (sensing range = $8m$)

(b) Coverage vs. sensing range of large disk (node number = 1000)

**Figure 5. Coverage variations with different node density and sensing range.**

round, under different sensing range. We can see that when sensing range is small, it will be energy-efficient. All three models will have lower power consumption, and the difference between them is not significant. With the growth of sensing range, the power consumption increases and Model II and Model III can have slower increasing speed than Model I. Model III can save energy by 30% when sensing range is increased to $12m$. We can draw the conclusion from this simulation that Model II can have better performance than Model I in both coverage ratio and energy consumption. Model III has the tradeoff of better energy-efficiency but worse performance in coverage ratio. It therefore suits some energy-critical applications.

## 5 Conclusions and Future Work

In this paper, we proposed two density control models for energy conserving protocol in sensor networks, using the adjustable sensing range of several levels. We extended the model in [21] by allowing the sensing ranges of sensors to be several-level adjustable, and based on this, to do the node scheduling, to reduce the overall sensing energy consumed and achieve a long-lived sensor network. The simulation results show that using Model II, we can achieve better performance in both coverage ratio and energy consumption. Using Model III, we can save energy by 20% and still have over 90% coverage ratio. In their recent work [22], Zhang and Hou extend the original node scheduling model to include different sensing ranges. The problem they try to deal with is how to let the model work when different sensor nodes may have different sensing ranges, but not to exploit the adjustable sensing ranges to achieve better performance which is our goal.

In the future, we will design the density control algorithm which could guarantee complete coverage based on our energy-efficient models, and also come up with the distributed density control protocol which could deal with other issues in energy consumption of sensor networks, such as transmission energy and calculation power consumption and also weighted cost among sensing, transmission and calculation.

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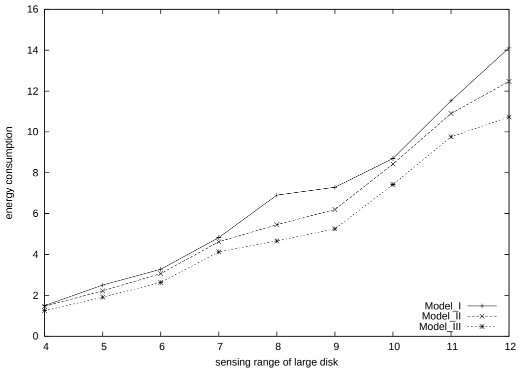

Figure 6. Energy variations with different sensing range.

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