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ENERGY-EFFICIENT NODE SCHEDULING MODELS IN SENSOR NETWORKS WITH ADJUSTABLE RANGES*

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In this paper, we study the problem of maintaining sensing coverage by keeping a small number of active sensor nodes and using a small amount of energy consumption in wireless sensor networks. This paper extends a result from [22] 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 [22], two new energy-efficient models with 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 and communication 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.

Keywords: Coverage; energy efficiency; node scheduling; sensor networks; simulation.

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 is one of the measurements of the *quality of service* (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

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formulations have been proposed, based on the subject to be covered (area versus discrete points) [12,13], 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 [14]. 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 that 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 total energy consumption of the active sensors 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 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 QoS 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 [15], 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 [18] 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 [20], [21] 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 [16], 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.

Zhang and Hou's work [22] 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 [19], 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 α. α 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 [17].

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). In [13], 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. A comprehensive survey on issues related to coverage in sensor network is given in [5].

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 [16], 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 adjustability 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 area of a node is defined as a circle of radius r_s (sensing range) centered at the location of this very node. In the following, we will denote this area covered by a node as its sensing disk.

The relationship of coverage and connectivity has been proved in [22], where the transmission range of sensor nodes being at least twice the sensing range guarantees network connectivity. In the following discussion, we use a more general way to guarantee network connectivity and calculate communication energy consumption. We assume all the working sensor nodes form a mesh network where a minimum spanning tree is constructed. All the communication is conducted among this tree. Therefore, each sensor node sets its communication power to reach its furthest on tree neighbor to maintain the connectivity.

3.2. *Proposed Node Scheduling Models*

In [22], 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

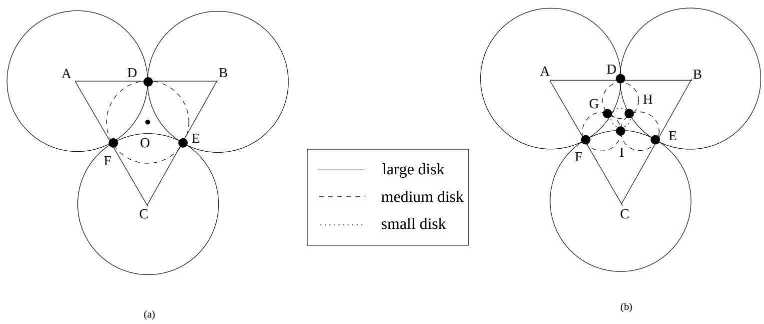


Fig. 1. (a) Coverage with two sensing ranges (Model II). (b) Coverage with three sensing ranges (Model III).

levels of adjustable sensing ranges. That is, we relax the condition of uniform sensing range to achieve better performance, i.e., less energy consumption for sensing per monitored area. One model (see Fig. 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 Fig. 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 radius of medium disk O to be $(1/\sqrt{3})r_{ls}$. □

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.

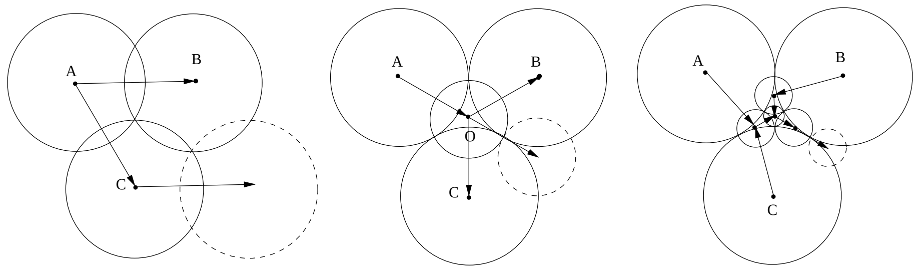
- Cover the area with non-overlapping large disks such that each disk “touches” six disks.
- The area enclosed by three adjacent disks is uncovered. Embed a small disk in the area so that it “touches” all three large disks. Three new uncovered areas are generated which are covered by three medium disks.

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 Fig. 1 (b) (Model III), the large disks centered at A, B, C are tangent to one another with the tangential points D, E, F. The small sensing disk centered at O is the circumcircle of them all with tangential points G, H, I. Its radius 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 radii of the medium disks are $(2/\sqrt{3} - 1)r_{ls}$. □

3.3. *Energy Consumption Analysis*

We consider the energy consumed by sensing and communication functions, do not include the calculation power consumption, and take the consumed power as zero when the sensor node is sleeping. We assume that the power consumed by the working sensor node to deal with the sensing task in a round is proportional to n's power of its sensing range, where parameter n is the path loss exponent $(2 \leq n \leq 6)$. We will use 2 and 4 as the values of n in the analysis, which represents different energy consumption models. (In the following, we will use r to indicate r_{ls} for convenience.) As to communication energy consumption, we assume all the working nodes in a round form a minimum spanning tree and each node should have enough power to communicate with its farthest on tree neighbor. We let the communication energy consumption to be proportional to n's power of the distance between a sensor and its farthest neighbor.



(a) (b) (c)

Fig. 2. Coverage and energy calculation of the models. (a) Model I. (b) Model II. (c) Model III.

3.4. *Sensing energy consumption*

1. *Model I*, Fig. 2 (a). The coverage area S_1 of the three sensors A, B and C is the area which could be monitored by at least one of the three sensor nodes. Therefore the area of S_1 is as shown in Eq. (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 $3r^2$ or $3r^4$, according to different n. (In the following, we use E to denote energy consumption when n is 2, $E^{'}$ for $n = 4$.) The energy consumption per area is as shown in Eq. (2) and Eq. (3), separately. Here the parameters μ_1 and μ_2 are power consumption per unit. We use *Joule* / r^2 (for E) and *Joule* / r^4 (for $E^{'}$) 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. *Model II*, Fig. 2 (b). In Model II, the coverage area S_2 covered by the four sensors can be calculated by the following Eq. (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 coverage area covered by these nodes. Eq. (5) and Eq. (6) are for different values of n.

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

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

3. *Model III*, Fig. 2 (c). In Model III, the coverage area S_3 of the seven sensors is equal to the one in Model II, so it can be calculated using Eq. (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 Eq. (7) and Eq. (8).

$$E_3 = \frac{(3r^2 + 3(7-4\sqrt{3})r^2 + (\frac{7}{3} - \frac{4\sqrt{3}}{3})r^2)\mu_1}{(\sqrt{3}+\frac{5}{2}\Pi)r^2} = 0.3380\mu_1 \quad (7)$$

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

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

3.5. *Communication energy consumption*

1. *Model I*, Fig. 2 (a). In Model I, every edge on the minimum spanning tree has the identical length. The lines in the figure illustrate one of the possible connections. Therefore, the communication energy consumption per area is the total energy of the three nodes divided by the coverage area, as shown in Eq. (9) and Eq. (10). (CE is for $n = 2$, CE' for $n = 4$ in the following.) The parameters μ_3 and μ_4 are independent of distance.

$$CE_1 = \frac{3(\sqrt{3}r)^2\mu_3}{S_1} = 1.0137\mu_3 \quad (9)$$

$$CE_1' = \frac{3(\sqrt{3}r)^4\mu_4}{S_1} = 3.0412r^2\mu_4 \quad (10)$$

2. *Model II*, Fig. 2 (b). In Model II, every large sensing disk node will choose the medium sensing disk node to connect, and the medium node can choose either a large one or the medium one in another cluster (we denote a medium disk and its three adjacent large disks as a cluster). All these edges have identical length. Therefore, the communication energy consumption per area is the total energy of the four nodes divided by the coverage area, as shown in Eq. (11) and Eq. (12).

$$CE_2 = \frac{4(\frac{2\sqrt{3}r}{3})^2\mu_3}{S_2} = 0.5566\mu_3 \quad (11)$$

$$CE_2' = \frac{4(\frac{2\sqrt{3}r}{3})^4\mu_4}{S_2} = 0.7421r^2\mu_4 \quad (12)$$

3. *Model III*, Fig. 2 (c). In Model III, every large sensing disk node will choose an adjacent medium sensing disk node to connect, and the small disk node will also choose a medium one. Two of the three medium nodes will choose the small one, the third will choose the nearest medium disk in the adjacent cluster (we denote a small disk and its adjacent three medium ones and three large ones as a cluster). The communication energy consumption per area is the total energy of the seven nodes divided by the coverage area, as shown in Eq. (13) and Eq. (14). To simplify the equation, we use r_m to denote radius of the medium disk in Model III, which is $(2-\sqrt{3})r$.

$$CE_3 = \frac{(3(\sqrt{r^2+r_m^2})^2 + 3(\frac{\sqrt{3}r}{3} - r_m)^2 + (2r_m)^2)\mu_3}{S_2} = 0.3955\mu_3 \quad (13)$$

$$CE_3' = \frac{(3(\sqrt{r^2+r_m^2})^4 + 3(\frac{\sqrt{3}r}{3} - r_m)^4 + (2r_m)^4)\mu_4}{S_2} = 0.3794r^2\mu_4 \quad (14)$$

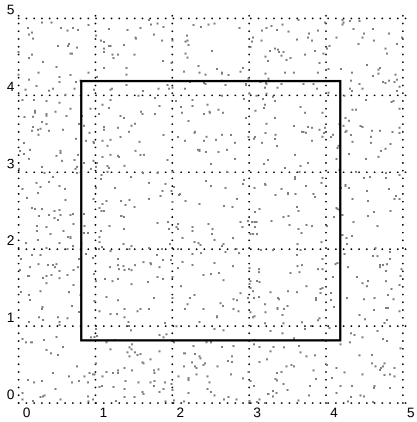
Model II and Model III introduce more working nodes with smaller sensing ranges, thus the communication range of each node is smaller. Communication energy consumption is proportional to n's power of this communication range. We can see from the above calculation that Model II and III have great energy reduction compared with Model I. The bigger n, the more significant this reduction.

4. Performance Evaluation and Simulation

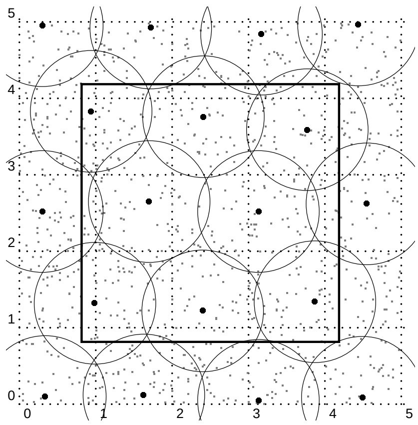
4.1. *Simulation Environment*

In order to evaluate our proposed models, we compare them with Model I proposed by Zhang *et al.* Since in [22], the optimal geographical density control (OGDC) algorithm, which is based on Model I, has been proved to have better performance than PEAS algorithm [21], the hexagon-based GAF-like algorithm, and also the sponsored area algorithm [16], we do not include the evaluation of these algorithms in the following evaluation.

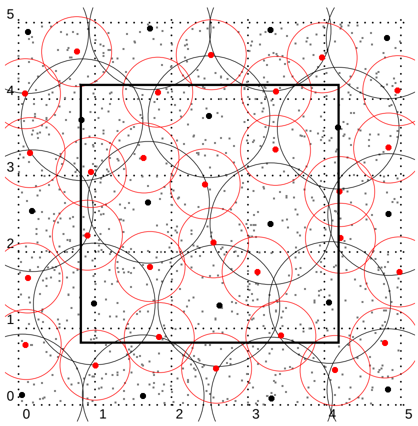
We customize a simulator to do the simulation. Since the issue we are to study is sensing coverage, some other issues such as mobility and MAC layer protocol are all ignored in our simulator. We set up our simulation in a $50 \times 50m^2$ network area. Sensor nodes are randomly distributed in the field initially and will remain stationary once deployed. To calculate sensing coverage, we divide the space into 500×500 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 $(50-r) \times (50-r)m^2$ 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. The energy consumption of the entire network in one round is sensing and communication energy consumption. We assume the energy consumed by sensing for a sensor is proportional to 2 or 4's power of its sensing range. Therefore, the sensing energy consumption of the entire network is the total sensing energy of all the working sensors in a round. Transmission energy consumption is usually more complicated to calculate. It includes transmitter's radio



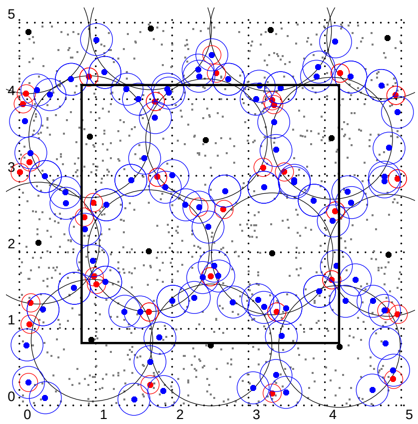
(a) Randomly deployed nodes



(b) Working nodes selected in Model I



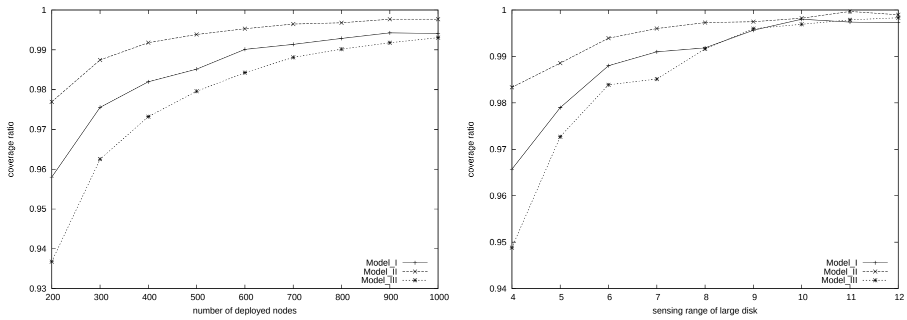
(c) Working nodes selected in Model II



(d) Working nodes selected in Model III

Fig. 3. 1000-node random network.

electronic energy consumption, power amplifier consumption and receiver's radio electronic energy consumption. It is well known that the propagation loss of radio signal is proportional to n's power of distance between the transmitter and receiver ($2 \leq n \leq 6$). To simplify the calculation, we only count transmitter's distance-dependant part of energy consumption, using 2 and 4 as n's value. Note that after the working nodes are selected, a minimum spanning tree can be constructed among them. We assume the energy consumed by communication for a sensor is proportional to 2 or 4's power of the distance from itself to its farthest on tree neighbor. Since communication only occurs occasionally and is different according to different communication schedule, the total energy consumption is not simply the sum of the two parts. We introduce parameter k to indicate the ratio of sensing energy in the



(a) Coverage vs. N ($r = 8m$)   (b) Coverage vs. r ($N = 1000$)

Fig. 4. Coverage variations with different node density and sensing range.

total energy consumption ($0 \le k \le 1$). In the simulation, we apply Li, Hou and Sha's local minimum spanning tree (LMST) [11] algorithm on the mesh formed by all the working sensor nodes. The LMST established for communication has very close performance to the minimum spanning tree constructed globally.

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, N, from 200 to 1000 to see the effect of node density on the models. (2) The sensing range of large disk r. 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). (3) Path loss exponent n. We use 2 and 4 in the simulation. (4) Ratio k. The ratio of sensing energy in the total energy consumption. We vary it from 0 to 1.

The performance metrics are: (1) The percentage of coverage, i.e., the ratio of the covered area to the total monitored area. We use the 500×500 bit map to denote coverage. (2) Sensing energy consumed in one round. We use n's power of the sensing range as its sensing energy in the comparison. (3) Communication energy consumed in one round. We use n's power of the distance from a sensor to its farthest neighbor on the minimum spanning tree formed by all the working nodes as its communication energy. (4) Total energy consumption. We use weighted sum of sensing and communication energy consumption to calculate the total energy.

4.3. *Simulation Results*

Fig. 3 (a) shows the random deployment of 1000 sensor nodes in $50 \times 50m^2$ area in our simulation. Fig. 3 (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.

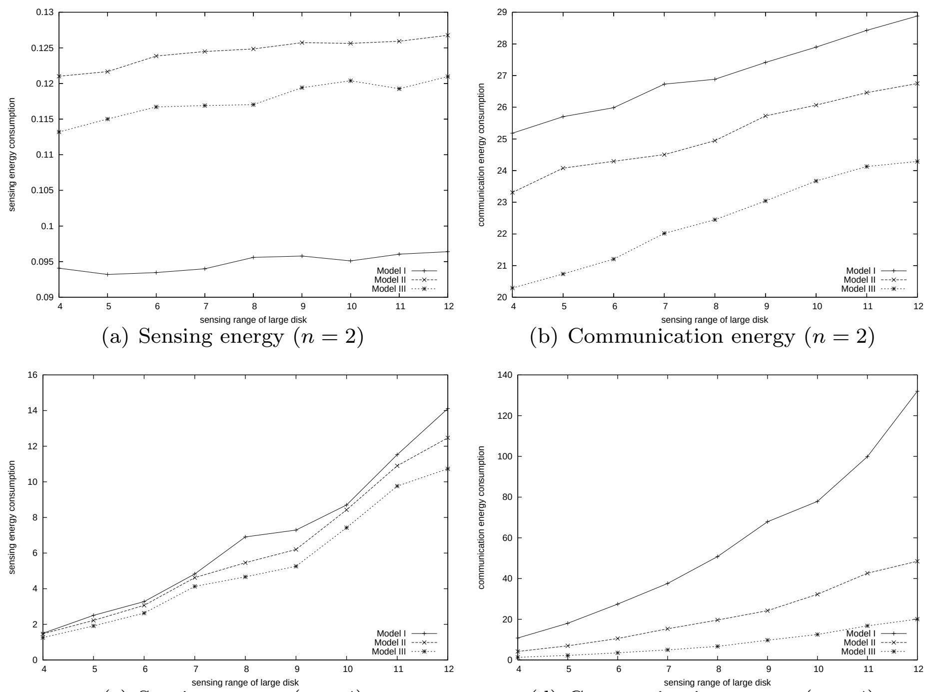
Fig. 4 shows the coverage variation when the node density or node sensing range changes. We can see from this that with different node density and sensing range, Model II can achieve better coverage ratio than Model I and Model III, especially when node density is low or sensing range is small. Model 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.

Fig. 5 is the energy consumption in one round, under different sensing range, using different n. (a) and (c) are sensing energy; (c) and (d) are communication energy. We can see that all the energy consumption increase with the growth of sensing range. Therefore when sensing range is relatively small, the sensor network is more energy-efficient. The bigger n, the greater reduction in both sensing and communication of Model II and III to Model I. In (a) and (c), when $n = 2$, the proposed models have greater sensing energy consumption than Model I, but still have less communication energy consumption. This is consistent with the above ideal case analysis. In (c), Model III can save sensing energy by 30% when sensing range is increased to $12m$. In (d), Model II can reduce Model I's communication energy by 60%, and Model III can achieve 85% energy reduction. This energy reduction is not subject to the change of sensing range. We can see that when n is 4, the proposed models have more significant energy saving compared with Model I.

Fig. 6 shows the total energy consumption using weighted sum of sensing and communication energy. Since the proposed models have better performance in communication energy reduction than in sensing energy reduction, the smaller the ratio k, the larger the total energy reduction. (a) is for $n = 2$. Model II and III have more sensing energy consumption than Model I. Therefore, when k is close to 1, the total energy of Model II or III exceeds that of Model I. (b) is for $n = 4$. Both Model II and III have less total energy consumption than Model I, and Model III is the most energy-efficient one.

We can draw the conclusion from this simulation as follows:

- The proposed Model II has better performance than Model I in both coverage ratio and energy consumption.
- The proposed Model III has the tradeoff of better energy-efficiency but worse performance in coverage ratio. It therefore suits some energy-critical applications.
- The larger the path loss exponent, the greater the energy saving of the proposed models.



(a) Sensing energy ($n = 2$)

(b) Communication energy ($n = 2$)

(c) Sensing energy ($n = 4$)

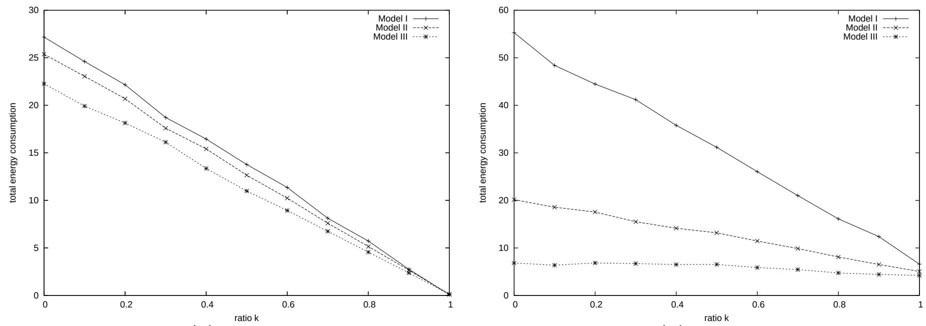
(d) Communication energy ($n = 4$)

Fig. 5. Energy variations with different sensing range ($N = 1000$).

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 [22] 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 significantly and still have over 90% coverage ratio. In their recent work [23], Zhang and Hou extend the original node scheduling model to include different sensing ranges. The problem they try to deal with is in 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 cost of communication and calculation.



(a) $n = 2$ (b) $n = 4$

Fig. 6. Total energy consumption with different ratio k ($r = 8m$, $N = 1000$).

References

1. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cyirci. Wireless sensor networks: A survey. *Computer Networks*, 38(4):393–422, 2002.
2. A. Boukerche, X. Cheng, and J. Linus. Energy-aware data-centric routing in microsensor networks. In *Proc. of the 8th international workshop on Modeling analysis and simulation of wireless and mobile systems*, pages 42–49. ACM Press, 2003.
3. N. Bulusu, J. Heidemann, and D. Estrin. GPS-less low cost outdoor localization for very small devices. Technical report, Computer science department, University of Southern California, 2000.
4. M. Cardei and D. Z. Du. Improving wireless sensor network lifetime through power aware organization. *accepted to appear in ACM Wireless Networks*, 2004.
5. M. Cardei and J. Wu. Coverage in wireless sensor networks. *accepted to appear in Handbook of Sensor Networks, M.Ilyas (ed.), CRC Press*, 2004.
6. D. Estrin, R. Govindan, J. S. Heidemann, and S. Kumar. Next century challenges: Scalable coordination in sensor networks. In *Proc. of ACM MOBICOM'99*, pages 263–270, 1999.
7. H. Gupta, S. R. Das, and Q. Gu. Connected sensor cover: Self-organization of sensor networks for efficient query execution. In *Proc. of ACM MOBICOM'03*, pages 189–200, 2003.
8. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Proc. of HICSS*, pages 4–7, 2000.
9. J. Hightower and G. Borriella. Location systems for ubiquitous computing. *IEEE Computer*, 34(8):57–66, 2001.
10. J. M. Kahn, R. H. Katz, and K. S. J. Pister. Next century challenges: Mobile networking for "smart dust". In *Proc. of ACM MOBICOM'99*, pages 271–278, 1999.
11. N. Li, J. Hou, and L. Sha. Design and analysis of an mst-based topology control algorithm. In *Proceedings of INFOCOM*, 2003.
12. X. Li, P. Wan, Y. Wang, and O. Frieder. Coverage in wireless ad-hoc sensor networks. *IEEE Transactions on Computers*, 52(6):753–763, 2003.
13. S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava. Coverage problems in wireless ad-hoc sensor networks. In *Proc. of INFOCOM'01*, pages 1380–1387, 2001.

14. E. Shih, S. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In *Proc. of ACM SIGMOBILE*, pages 272–287, July 2001.
15. S. Slijepcevic and M. Potkonjak. Power efficient organization of wireless sensor networks. In *Proc. of ICC 2001*, pages 472–476, June 2001.
16. D. Tian and N. D. Georganas. A coverage-preserving node scheduling scheme for large wireless sensor networks. In *Proc. of First ACM International Workshop on Wireless Sensor Networks and Applications*, pages 32–41, 2002.
17. X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill. Integrated coverage and connectivity configuration in wireless sensor networks. In *Proc. of the first international conference on Embedded networked sensor systems*, pages 28–39. ACM Press, 2003.
18. Y. Xu, J. Heidemann, and D. Estrin. Geography-informed energy conservation for ad hoc routing. In *Proc. of ACM MOBICOM'01*, pages 70–84, July 2001.
19. T. Yan, T. He, and J. A. Stankovic. Differentiated surveillance for sensor networks. In *Proc. of ACM SenSys'03*, pages 51–62, November 2003.
20. F. Ye, G. Zhong, S. Lu, and L. Zhang. Energy efficient robust sensing coverage in large sensor networks. Technical report, UCLA, 2002.
21. F. Ye, G. Zhong, S. Lu, and L. Zhang. Peas: A robust energy conserving protocol for long-lived sensor networks. In *Proc. of the 23nd International Conference on Distributed Computing Systems (ICDCS)*, page 28, 2003.
22. H. Zhang and J. C. Hou. Maintaining scheme coverage and connectivity in large sensor networks. Technical report, UIUC, 2003.
23. H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. In *Proc. of NSF International Workshop on Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless, and Peer-to-Peer Networks*, 2004.