Employing Energy-Efficient Patterns for Coverage Problem to Extend the Network Lifetime

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Abstract. The coverage problem is a fundamental issue in wireless sensor networks. It has attracted considerable attention recently. Most node scheduling patterns utilize the adjustable range of sensors to minimize the sensing energy consumption, and thus extend the network lifetime. However, a large source of the consumption of the sensor communication energy is not strictly taken into account. In this paper, we introduce two energy-efficient patterns that are used to minimize the communication energy consumption of a sensor network, and simultaneously, maintain a high degree of coverage. Moreover, the proposed patterns have a structure that is easy to design and apply to practical applications. Calculations and extensive simulation are conducted to evaluate the efficiency of the new patterns compared to existing ones in terms of various performance metrics.

Keywords: coverage problem; node scheduling; energy-efficiency; wireless sensor networks.

1 Introduction

Modern technology has enabled a new generation of wireless sensor networks that are feasible for a wide range of commercial and military applications. A wireless sensor network (WSN) is composed of a large number of autonomous sensors that are densely deployed into a target sensing field to monitor physical phenomena of interest [1]. Replenishing power resources is a difficult and impossible task in most cases, since each sensor has a limited power battery. Energy-saving optimization is an important criteria to evaluate the success of WSNs. Recent analysis [4] shows that each sensor uses a large portion of power for communication. Therefore, this paper considers the problem of how to minimize the communication energy consumption by adopting two strategic coverage patterns.

A fundamental issue in WSNs is the coverage problem, that concerns how well the target sensing field is monitored or tracked by sensors. In this paper, we consider the full coverage problem, in the sense that every point in the target sensing area is covered by at least one sensor. On the other hand, there are two mechanisms in sensor deployment: deterministic deployment and random deployment. In deterministic deployment,

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a sensor can be placed exactly at a defined position in the target sensing field. In contrast, the position of a sensor is not known a priori in random deployment. Our proposed strategic patterns are useful in deterministic deployment as well as random deployment. Another important consideration in WSNs is the node scheduling problem, as it has a significant impact on extending the network lifetime. A node scheduling mechanism operates, so that a set of active sensor nodes is selected to work in a round, another random set is selected in another around, as long as the coverage goal is met [12]. The results of this paper can be used as a guideline to select active sensors in each round, so that two conflicting goals are satisfied simultaneously: minimizing the communication energy consumption and keeping a high degree of coverage.

As shown in [4], power consumption can be divided into three domains: sensing, communication, and data processing. Recent coverage patterns only consider how to minimize the overlapped sensing areas of sensors, and thus optimize the sensing energy consumption of WSNs. In [3, 12, 14] the authors utilize the adjustable sensing range of sensors to achieve significant improvement in coverage efficiency. Recently, the authors in [14] proposed the optimal sensing energy patterns using two adjustable sensing ranges. These patterns outperform the existing ones with respect to various performance metrics. However, none of the previous work considered patterns that minimized communication energy consumption. Communication tasks are indispensable since sensors have to forward and receive data from other sensor nodes hop-by-hop. Communication energy consumption in WSNs becomes more critical in applications that require high rate data collection in real-time such as [10] and [8]. Therefore, communication energy consumption should be taken into account when designing energy-efficient coverage patterns.

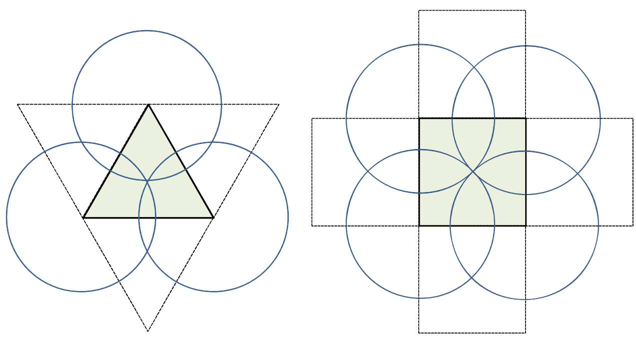
In this paper, we also propose a node scheduling pattern, but we concentrate on minimizing the communication energy consumption that is the most important resource of WSNs. In summary, this paper makes the following key contributions:

- Novel patterns are constructed, so that they can be used in deterministic deployment, as well as in random deployment. In deterministic deployment, the patterns become a strategic plan to design an efficient WSN. In cases where sensors are randomly deployed, our proposed patterns aid a node scheduling mechanism to select active nodes in each round.
- All the patterns have structures that are easy to implement and design due to their simplicity. This makes our patterns practical.
- To the best of our knowledge, when considering an energy-efficient pattern for the coverage problem, we provided the best patterns in terms of communication energy consumption.

The remainder of this paper is organized as follows. In section 2, we discuss related work. Section 3 presents the system model and assumptions while Section 4 presents our proposed patterns. Section 5 shows the performance evaluation result. Finally, we conclude our work in section 6.

2 Related Work

A survey on the energy-efficient coverage problem is researched by Cardei and Wui [4]. The paper summarizes various problems on coverage area as well as their corresponding solutions. One of the mechanisms to reduce the redundant energy is using a node scheduling strategy. In this strategy, the network is scheduled to operate in turn, in the sense that one set of sensors is selected to monitor fully the entire target sensing field, and another set will be selected at another time, after the current set of sensors goes into a dormant state. Coverage ratio is one of the measurements of the system's quality of service. It plays an important role in evaluating whether or not a WSN topology is good. There is always a lower bound of coverage ratio. If the coverage ratio falls below this threshold, the network may not operate correctly. Therefore, the major challenge for the success of WSNs is designing an energy-efficient model that provides a high degree of coverage.

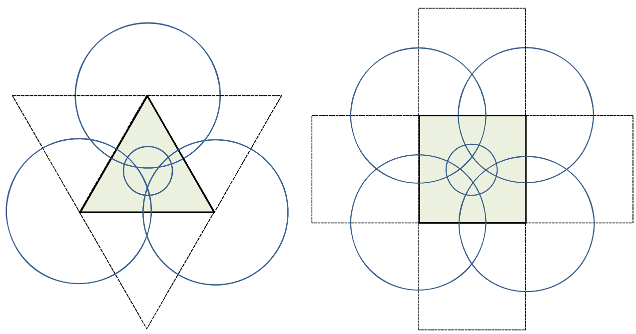


(a) Pattern A1. (b) Pattern B1.

Fig. 1. Coverage patterns with uniform sensing range

Another approach to extend the network lifetime is using sensors with adjustable ranges. In [12], two node scheduling patterns are proposed to reduce the sensing energy consumption of WSNs. The authors construct the patterns based on regular polygons-tiles that cover the entire target sensing field without overlap. As shown in Fig. 1, pattern A1 is based on a regular triangle tile and pattern B1 based on a square tile. The authors in [14] introduce the concept of coverage density that is used as a standard metric to evaluate the efficiency of a pattern in terms of coverage efficiency. Thus, they proposed the optimal sensing energy consumption patterns, using two adjustable sensing ranges, as shown in Fig. 2. The ratio between the large disk's sensing range and small disk's sensing range of patterns A2 and B2 are $\sqrt{31}$ and $\sqrt{5}$, respectively. These patterns have been shown to outperform prior ones with respect to various performance metrics. Similar to [3, 12], and [14], we consider the problem of energy-efficient area coverage patterns. However, this paper supplements the important limitation of previous studies by introducing patterns that are considered to be the best among the existing ones in terms of communication energy consumption.

The analysis of the power usage for the WINS Rockwell seismic sensor shows that the power usage for communication is between 0.74 W and 1.06 W, for the idle state it is 0.34 W, for the sleep state 0.03 W, and for the sensing task 0.02 W [9]. Thus, the communication energy consumption is much higher than the sensing energy consumption. Recently, more applications such as monitoring industrial processes, geophysical environments, and civil structures (buidings, bridges, etc), require high-data rate signals [10, 8]. A key challenge in those applications is how to collect efficiently those fidelity data subject to limited radio bandwidth and the battery of sensors. Therefore, finding an energy-efficient pattern in terms of communication energy consumption is crucial in such those applications.



(a) Pattern A2. (b) Pattern B2.

Fig. 2. Optimal coverage patterns with 2 adjustable sensing range

In [2], Bai et al. propose deployment patterns to achieve full coverage with three-connectivity and full coverage with five-connectivity, under different ratios of sensor communication range over the sensing range for WSNs. The authors in [15] and [13] consider the *k-coverage* problem with any arbitrary sensing shape and find the weak sub-regions degrading the overall coverage performance. Various related coverage problems have been discovered recently. Examples include the coverage problem in three dimensional space [6], coverage for estimating localization error [11], and barrier coverage problem [13].

3 System Model and Assumptions

3.1 System Model

In this paper, we assume that the sensor nodes are randomly deployed in a two-dimensional target sensing field, where each node uses a Global Positioning System or a localization scheme to knows its position. The sensing area of each sensor is a disk of a given sensing range. The sensors are in charge of monitoring a target sensing field which is assumed very large compared to the sensing area of a sensor, and thus we can ignore the boundary effect of the target sensing field.

We construct a minimal spanning tree among active nodes when calculating the communication energy consumption. Each node adjusts its communication range to the farthest node on the tree to guarantee network connectivity. We also assume that the energy consumed by communication for a sensor is proportional to the square of the distance from itself to its farthest node in the minimum spanning tree.

Finally, since our sensor deployment is random deployment, we may not find a sensor that has the exact location in the pattern. In this case, we select a sensor that is the closest to the ideal position in the corresponding pattern. Similar to previous studies, we construct the patterns based on a regular polygons-tile that cover the whole target sensing field without overlap. We also suppose that all tiles are covered in the same manner. Sensors are placed at the vertices of the polygons and the circles represent the sensing areas of sensors. All patterns proposed in [12] and [14] have the structure of pattern A1 or pattern B1. Therefore, we select these two basic patterns as the starting point of our procedure to construct the new patterns.

3.2 Important Definitions

Before going into the details of the proposed patterns, we introduce three important metrics that are used in [14] to compare the efficiency among patterns in terms of coverage density and communication energy consumption.

Definition 1. Coverage density (D) is the ratio of the total area of the parts of disks inside the tile divided by the area of the tile. Given a coverage model as in Figure 3, the coverage density $D = \frac{S_1+S_2+S_3}{S_{I_1I_2I_3}}$, where S_1, S_2, and S_3 denote the areas of parts of disks of sensors I_1, I_2, and I_3 inside the tile, respectively; $S_{I_1I_2I_3}$ denotes the area of the triangular tile.

Definition 2. Sensing energy consumption per area (SECPA) is the part of the sensors' sensing energy used by the nodes inside a tile divided by the tile's area. We suppose that the sensing energy consumption is proportional to the area of sensing disks by a factor of μ_1, or the power consumption per unit. Then, SECPA is $SE = D.\mu_1$

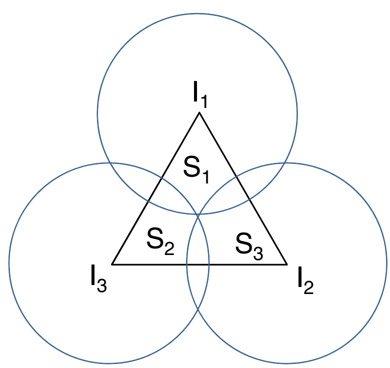


Fig. 3. Coverage Density

Definition 3. Similar to SECPA, communication energy consumption per area (CECPA) is the part of the sensors' communication energy used by the nodes inside a tile divided by the tile's area.

4 Proposed Patterns

4.1 Energy-Efficient Pattern Based on the Hexagonal Tile

As presented in [15], pattern A1 is the optimal topology, in the sense that it provides the minimum number of sensors used to cover fully the entire target sensing field, if all sensors have the same sensing range. However, the communication energy consumption of pattern A1 is considerably high. Therefore, to retain the advantages of pattern A1, and simultaneously improve the communication energy consumption, we construct another pattern, A3, based on a hexagonal structure, as shown in Fig. 4.

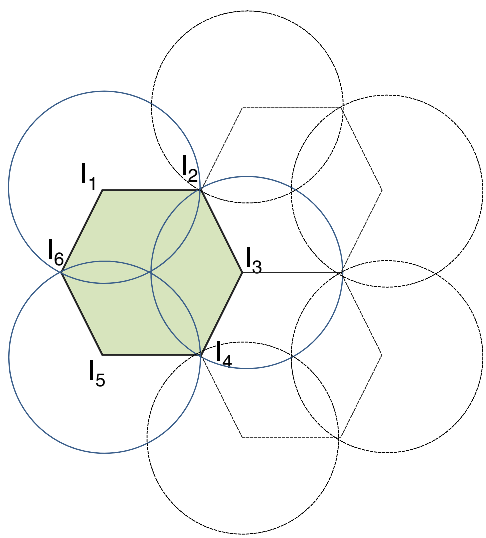


Fig. 4. Pattern A3

As opposed to the previous patterns, we assign sensors to different tasks. In Fig. 4, only three sensors placed at I_1, I_2, and I_5 retain both roles: sensing the monitored field and continuously communicating with other sensors. Conversely, sensors placed at I_2, I_4, and I_6 only need to turn on their communication function. The main reason for this strategy is that the topology of all sensors retaining both roles is the same with the topology of pattern A1. Therefore, the coverage density and the sensing energy consumption are equal to pattern A1's coverage density and sensing energy consumption, respectively. An interesting point we found here is that due to the symmetry, sensors in pattern A3 can take turns to switch on/off their sensing ability. For example, in the first round, sensors at I_2, I_4, and I_6 turn on their sensing ability, while sensors at I_1,

I_3, and I_5 turn off their sensing ability. In the next time slot, sensors placed at I_2, I_4, and I_6 take on the sensing responsibility, while sensors at I_1, I_3, and I_5 can safely turn the function off. Therefore, the energy consumption is more balanced between sensor nodes.

We apply the same method to calculate the coverage density D and sensing energy consumption per area, similar to [14]. For pattern A3, the coverage density and sensing energy consumption are:

$$D_{A3} = 2\Pi/3\sqrt{3} \approx 1.2091$$

$$SE_{A3} \approx 1.2091\mu_1,$$

where μ_1 is the sensing power consumption per unit.

We assume that all sensors are involved in communication and construct a minimal spanning tree that spans all the sensors to calculate the communication energy consumption of this pattern. We assume that the energy consumed by communication for a sensor is proportional to the square of the distance from itself to its farthest neighbor on the tree by a factor of μ_2, where μ_2 is the communication power consumption per unit. We ignore the edge effect and calculate CECPA for the case of infinite grid, as for the estimation of coverage density. The communication energy consumed by each node in each rectangle is $\frac{1}{3}I_1{I_2}^2\mu_2$, since each node contributes to 3 hexagonals. Finally, the CECPA of pattern A3 is calculated as follows:

$$CE_{A3} = \frac{\frac{6}{3}I_1{I_2}^2\mu_2}{S_{I_1I_2I_3I_4I_5I_6}} \approx 0.7698\mu_2,$$

where $S_{I_1I_2I_3I_4I_5I_6}$ denotes the area of the hexagonal tile.

4.2 Energy-Efficient Pattern Based on the Square Tile

According to [14], the patterns based on a square tile are optimal with respect to the communication energy consumption per unit area. Moreover, a rectangular placement grid seems to be more convenient in practice, especially in the case of covering a rectangular area. As shown in [14], pattern B1 has a SECPA that approximates to $1.57\mu_1$, while the CECPA is μ_2. Although the communication energy consumption of pattern B1 is efficient, we can further improve this pattern to lower communication energy consumption.

Based on coverage pattern B1, we construct another pattern, as shown in Fig 5. Similar to pattern A3, we also assign sensors to different roles. Sensors at I_1, I_3, I_5 and I_7 retain both sensing and communication functions, while sensors placed at I_2, I_4, and I_6 only need to turn on their communication function. The coverage density and SECPA of pattern B3 are similar to the coverage density and SECPA of pattern B1, which are $D_{B3} \approx 1.5708$ and $SE_{B3} \approx 1.5708\mu_1$, respectively, because the pattern B3 is similar to pattern B1 with respect to sensing energy consumption.

We also construct the MST that spans all the sensors to calculate the communication energy consumption of pattern B3. Each of the four nodes, I_1, I_3, I_5 and I_7, contributes to four rectangles. Thus, the communication energy consumed by each node in each

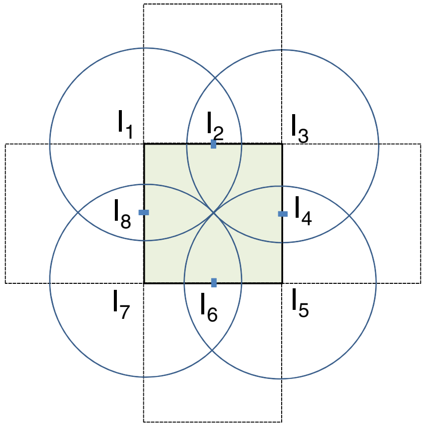


Fig. 5. Pattern B3

rectangle is $\frac{1}{4}I_1{I_2}^2\mu_2$. Each of the four nodes I_2, I_4, I_6 and I_8, contributes to only two rectangles. Thus, the communication energy consumed by each node in each rectangle is $\frac{1}{2}I_1{I_2}^2\mu_2$. Finally, the CECPA of pattern B3 can be calculated using the following equation:

$$CE_{B3} = \frac{\frac{4}{4}I_1{I_2}^2\mu_2 + \frac{4}{2}I_1{I_2}^2\mu_2}{S_{I_1I_3I_5I_7}} \approx 0.75\mu_2,$$

where $S_{I_1I_3I_5I_7}$ denotes the area of the square tile, and μ_2 is the communication power consumption per unit.

Table 1 summarizes the SECPA and CECPA of six patterns. We see that patterns A2 and B2 have the lowest value of sensing energy consumption, whereas patterns A3 and B3 are the best in terms of communication energy consumption. In the next section, we will compare the energy efficiency of all patterns with extensive simulation.

Table 1. Energy consumption per area for different patterns

Type	*SECPA*	*CECPA*
Pattern A1	$1.20\mu_1$	$1.15\mu_2$
Model A2	$1.10\mu_1$	$1.15\mu_2$
Pattern A3	$1.20\mu_1$	$0.7698\mu_2$
Pattern B1	$1.57\mu_1$	μ_2
Pattern B2	$1.17\mu_1$	μ_2
Pattern B3	$1.57\mu_1$	$0.75\mu_2$

5 Performance Evaluation

5.1 Simulation Environment

To evaluate the efficiency of our new patterns (patterns A3 and B3), we compare them to the previous ones: pattern A1 proposed by Zhang et al. [15], patterns B1, A2, and B2 proposed by Zalyubovskiy et al. We use the same simulation environment as in [12,14]. We randomly deployed 1000 sensors in a $50m \times 50m$ area. The sensing range of the large disk, R, varies from 4 m to 12 m. We first construct a minimal spanning tree among the working nodes to estimate the communication energy consumption. We assume that the energy consumed by communication for a working sensor is proportional to n's power of the distance to its farthest neighbor in the tree ($n = 2, 4$). As mentioned earlier, we suppose that we can find a sensor at any desirable position. Since this assumption may not hold in practical applications, we select sensors that are closest to the defined position in our ideal patterns. We use the following metrics to compare the performance of all patterns:

1. Sensing energy consumption per area (SECPA) in one round.
2. Communication energy consumption per area (CECPA) in one round.
3. Total energy consumption per area (TECPA) in one round.

We use the energy cost model as in [16], to estimate the TECPA of the entire network. In this model, the total energy consumption of each working node is calculated by the following formula:

$$E = kS(R)^x + (1-k)T(R)^y + C,$$

where $S(R)$ and $T(R)$ denote the sensing range and communication range of a sensor, respectively; x and y are constants between 2 and 4; k is a constant, such that $0 \leq k \leq 1$. The energy consumed by the idling radio and processor of each sensor is a constant, C. Similar to [16], we select $x = y = 4$ and $C = 2000$ for our simulation.

5.2 Simulation Results

As shown in Figure 6, the simulation results about the sensing energy consumption are correlated with the theoretical analysis in section IV. Patterns A2 and B2 are the best patterns in terms of the sensing energy consumption. The sensing energy consumption of patterns A3 and B3 are equal to patterns A1 and B1, respectively, as the set of sensor nodes, which turns on sensing ability in patterns A3 and B3, is similar to the set of sensor nodes in patterns A1 and B1.

Figures 7 shows the communication energy consumption of all patterns when the path loss exponent is $n = 2$ and Figures 8 shows the communication energy consumption when the path loss exponent is $n = 4$. In both cases, patterns A3 and B3 are the best patterns with respect to communication energy consumption, since the average distance between neighbor nodes in patterns A3 and B3 is smaller than other patterns. Thus, the communication energy consumption is minimized.

Figure 9 shows the total energy consumption of six patterns. We can see that our proposed patterns A3 and B3 outperform the other patterns in terms of the total energy consumption in most cases. When the ratio $k > 0.7$, the total energy consumption of pattern B3 is not as good as for pattern A2 and A3 due to its high sensing energy consumption. Therefore, pattern B3 is the most preferred in a WSN that has frequent traffic, while pattern A2 and A3 are suitable for WSNs that have low traffic.

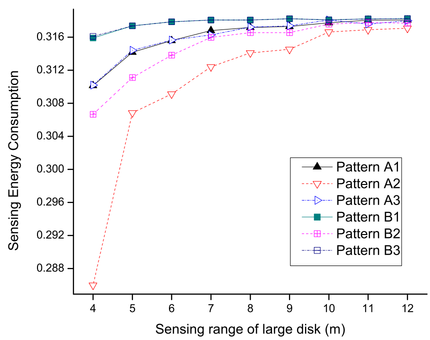


Fig. 6. Sensing energy consumption

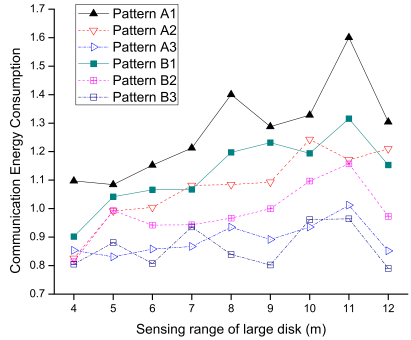


Fig. 7. Communication energy consumption ($n = 2$)

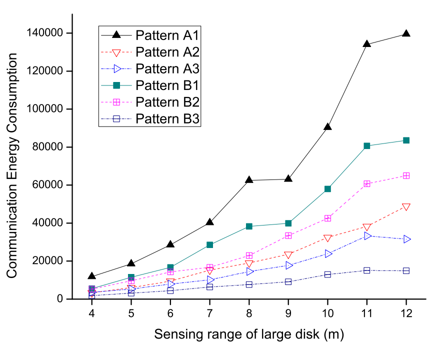


Fig. 8. Communication energy consumption ($n = 4$)

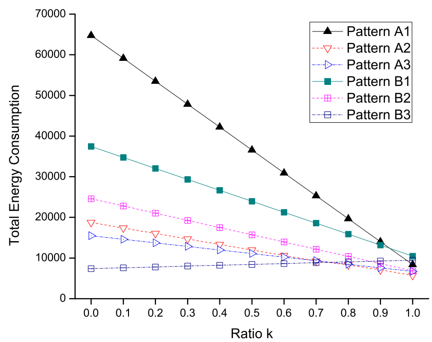


Fig. 9. Total energy consumption

6 Conclusion

In this paper, we constructed energy-efficient node scheduling patterns under the condition of a high ratio of sensing coverage. Our mathematical results and simulation show that our two new proposed patterns A3 and B3 significantly improve energy consumption compared to patterns A2 and B2 that were previously known as the best. Our future research considers scheduling algorithms employed on the proposed patterns and improve the sensing energy consumption as well as minimizing the number of deployed sensors.

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