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Coverage Aware Scheduling in Wireless Sensor Networks: An Optimal Placement Approach

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Abstract Area coverage is an important issue in wireless sensor networks, which reflects how well an area is monitored or tracked by sensors. But, since a sensor network has restricted energy resources, energy efficiency is vital for this area coverage. One of the most efficient solutions to provide energy-aware area coverage is scheduling. That is, without any assumption about sensors' locations, only a distributed and parallel scheduling method determines which sensors should be on and which ones should be off in each decision period. The ultimate objective is to maximize network lifetime and keeping a target level of area coverage. A major part of the algorithms proposed in this field, schedule a sensor node activity based on its neighbors' information. Such information includes the distances of a node from its neighbors, the number of its active neighbors, etc. Indeed, message exchange is essential in the implementation of these algorithms which causes to increased energy consumption. In this paper, we propose a distributed scheduling algorithm, at which, each node itself decides to make its sensor on or off based on its location information and the node density over the target area. For this purpose, we first compute the minimum number of nodes that are enough to cover the target area. Then we obtain the best locations for theses nodes. Based on these computed location the area is partitioned into some sub-area, each one coverable by only one sensor. Then in each sub-area, a local scheduling procedure schedules the activation order of sensor. Simulation results show that the proposed algorithm, called CAOP, can maximize the network lifetime while maintaining complete area coverage.

Keywords Area coverage · Scheduling sensor activity · Network lifetime

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1 Introduction

Wireless sensor networks (WSNs) consist of small-sized sensor nodes [1] and have been used in many applications such as vehicle tracking, danger alert and battlefield surveillance. Generally the wireless sensor nodes are equipped with finite power batteries that can be deployed cheaply and rapidly for monitoring the environment events. In such a network replacing node battery is impossible, hence, in order to prolong the network lifetime and to keep a high degree of reliability, a type of redundancy is provides by deploying a high density of sensors [2]. But, if all the sensor nodes are active at the same time, a major part of nodes' energy will be consumed due to an extra amount of message exchanges. Obviously, this can lead to fast depletion of nodes' energy and ending the network life. To prevent the nodes from unnecessary activities, we can use some scheduling algorithms. Scheduling algorithms are applied to schedule nodes to be activated alternatively to save the overall energy of the system. These scheduling algorithms are often aware of some design goals such as connectivity, coverage, energy saving and so on. That is, since the scheduling policy makes some sensors on and makes others off, naturally it may cause to reduced connectivity and coverage. Hence, a subset of nodes that are kept active for sensing and communication must ensure coverage, connectivity and other design objectives.

The coverage concept is one of the most fundamental issues in WSNs, which directly affects the quality of service (QoS). The coverage indicates how well the deployed sensor nodes can track a set of targets. Sensor activation scheduling under constraint on covering of targets is called the coverage problem in the literature. Generally, there exist three types of coverage in a WSN: point coverage, barrier coverage and area coverage [3]. Point coverage refers that the separate target points can be covered at any time [4]. The objective of barrier coverage is to minimize the probability of undetected penetration through the sensor network [3]. In the area coverage problem, the goal is to cover some areas. In all the proposed solutions the goal is to find a minimum set of active nodes that can maintain coverage and connectivity of the network in a suitable level while the consumption of the energy by the sensor nodes is as balanced as possible.

By far, many coverage scheduling algorithms have been proposed. Some of these algorithms [5] assume that the nodes know their locations by using some devices or techniques. Others [6] adopt that the distances between nodes can be achieved by using the received signal strengths. Some others [7] consider some mobile nodes with controllable mobility. Some other researchers have also suggested coverage control algorithms without usage of any location, distance or angle information of the sensor nodes.

From other point of view, a sensor activity scheduling algorithm can be either centralized or distributed. A distributed scheduling protocol can be easily expanded to large-scale sensor networks, so it is more desirable. It is often assumed in these protocols that the time is divided into rounds. At the beginning of each round, all sensor nodes wake up and must make their activity decisions the current round. This decision stage is based on the message exchanges. Moreover, at the end of a round, all sensors must be activated and decision stage is required to be repeated in the next round. Athwart, the power consumption rate of the message exchanges may be very high, if the network scale is great.

This paper assumes that any sensor node knows its location and then tries to design an energy-aware area coverage scheduling algorithm. The proposed algorithm follows a distributed approach and is called Coverage Aware scheduling for Optimal Placement of sensors (CAOP). Its design goal is to maintain area coverage and to prolong the network lifetime by efficient energy consumption.

Rest of this paper is organized as follows. In the next section, some existing scheduling-based algorithms in WSN coverage problem are reviewed. Section 3 brings the required preliminaries for this work. In Sect. 3, the proposed algorithm (CAOP) is given. Section 4 evaluates the performance of the proposed algorithm and compares its outcomes with other related works. Finally, in Sect. 5, this paper is concluded.

2 Related Works

Coverage scheduling has received many attentions in recent years. In [8], the objective is to maximize the network life time while full coverage of the targets is guaranteed. The authors propose an algorithm to divide all the wireless sensor nodes into a maximum number of disjoint set covers (DSCs), where every cover can monitor all the targets. In other words, it claims solving a NP-complete problem in which sensing coverage as well as a longer network lifetime can be guaranteed by alternating switching between DSCs. The network coverage problem is closely related to network energy consumption. Most of the related research to reduce the energy consumption focuses on communication protocols. They classify the coverage problem from different angles, explain the evaluation metrics of coverage control algorithms, and analyze the relationship between coverage and connectivity. In another research [9], a distributed, probing-based density control algorithm, named PEAS, was proposed for robust sensing coverage. As discussed in PEAS, a sensor resolves to sleep, if it finds at least one active neighbor within its probing area. This is performed by exchanging probe messages. The probing area of a sensor is a disk centered at the sensor with the radius the probing range. In PEAS different area coverage can be achieved by adjusting the probing range of nodes. Scantly algorithms aim to satisfy primary coverage based on mathematical model. However, in [10] a mathematical optimization model with an applicable and efficient solution method is proposed, which uses sensor places and data routes to WSN design decisions. The authors present two heuristic linear programming methods for the solution of the model.

In many activity scheduling protocols, the subject to be covered is the complete area, while other protocols allow that some space points need not to be covered. The analysis and simulations in [11, 12] have shown that the network coverage lifetime can be prolonged if only preserving partial coverage other than preserving complete coverage is required. Network coverage lifetime is often defined as the duration of the network established time to the time that the network coverage cannot be satisfied when all sensors are active.

Therefore, in order to prolong the network lifetime a WSN should be deployed with high density of sensors and then scheduled sensor activity. Several node-scheduling schemes for coverage problems in WSN based on neighbor information. Such information includes the distances between itself and its neighbors, the number of its active neighbors, etc. For example, in [13, 14], a sensor decides to inactive if it finds at least one active neighbor. Neighbor distance-based scheduling and neighbor number-based scheduling are two approaches for sensor nodes making activity decision at each decision stage. In [15], a closest-neighbor-based scheduling algorithm is proposed, where a sensor node is qualified to inactive if the distance to its closest active neighbor is less than a defined threshold. The relation between the coverage of a sensor's sensing disk and the number of its sensing neighbors is analyzed in [16], where a sensor node is a sensing neighbor of another one if their Euclidean distance is not greater than the sensing range. This work suggests that if a sensor's sensing disk is covered by its sensing neighbors, then we need to choose at least three sensing neighbors and at most five sensing neighbors to cover the sensor's sensing disk.

3 Assumptions and Preliminaries

In this section, we first state all the assumptions taken into account in this work and then bring some preliminaries about the sensor coverage models in the WSNs. This preliminary focuses on available coverage models in WSN community and describes some related terms and parameters.

3.1 Assumptions

As other works, we assume that the timeline is divided into consecutive rounds. At the first round, all sensors are active and are informed about their activation round. The blow assumptions are considered in this paper:

- Sensor node deployment in the coverage area is random i.e. their locations are set by independent random procedures.
- Each node is aware of its location and all the nodes are able to communicate with each other.
- All the sensors have a same sensing range which is denoted as R_s.
- All the sensors are aware of the number of nodes deployed in the environment which is denoted as Nodes_Number.

3.2 Coverage Models in Wireless Sensor Networks

In the study of WSN coverage control, two kinds of sensing model are mainly applied: binary sensing model and probability sensing model [17]. The binary sensing model assumes that if an event occurs at a distance less than or equal to sensing range, the sensor will deterministically detect this event. According to the binary sensor model, addressed in [18], the probability of sensing an event occurred at point P(x, y) by sensor s_i is denoted by $C_{xy}(s_i)$:

$$C_{xy}(s_i) = \begin{cases} 1 & \mathit{if}\ d(s_i, P) \le r_s \\ 0 & \mathit{otherwise} \end{cases} \tag{1}$$

In which, $d(s_i, P)$ is the Euclidean distance between s_i and P.

$$d(s_i, P) = \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{2}$$

In the actual application environment, due to the interference of the environmental noises and the drop of the signal intensity, the detection ability of the sensor nodes is unstable and hence a precise detection model is introduced as in Eq. (3).

$$C_{xy}(s_i) = \begin{cases} 1 & d(s_i, P) \le r - r_e \\ e^{-\frac{\alpha_1 \gamma_1 \beta_1}{\gamma_2 \beta_2 + \alpha_2}} & r - r_e \le d(s_i, P) \le r + r_e \\ 0 & otherwise \end{cases} \quad (3)$$

where $r_e (0 < r_e < r)$ is a measure of uncertainty in the sensor detection, α_1, α_2, β_1, β_2, γ_1 and γ_2 are parameters related to the characteristic of sensor nodes [19]. Two parameter γ_1 and γ_2 are defined by Eqs. (4)–(5).

$$\gamma_1 = r_e - r + d(s_i, P) \quad (4)$$

$$\gamma_2 = r_e + r + d(s_i, P) \quad (5)$$

If $r_e \approx 0$, we use the binary sensor detection model, on the other hand, if $r_e > 0$, the probabilistic sensor detection model is used and $r_e$is not negligible. Assume the network is digital discrete with $m \times n$ pixels, the pixel's coordinate is (x, y). In this case, it is necessary to overlap the sensor detection area to compensate for the low detection probability. Thus, to increase the measuring probability, more sensor nodes are needed. Expressing the set of sensor nodes as $s_{cov} = \{s_1, s_2, \ldots, s_n\}$, the coverage in this case will be given by:

$$P_{xy}(s_{cov}) = 1 - \prod_{s_i \in s_{cov}} \left(1 - C_{xy}(s_i)\right) \quad (6)$$

Finally, the coverage rate of the sensor set s_{cov} is defined as follows:

$$R_{cov}(s_{cov}) = \frac{\sum_{x=1}^{m} \sum_{y=1}^{n} P_{xy}(s_{cov})}{m \times n} \quad (7)$$

4 Coverage Aware Scheduling by an Optimal Placement Approach

In this section, we present details of COAP, a novel coverage-aware scheduling algorithm for WSNs. In summary, every node in CAOP has the following tasks and activities. First, based on nodes' sensing range and dimensions of the target area, it computes the minimum number of nodes required for covering whole the area. The assumed places for these nodes are considered as optimal places. Second, based on density of available sensing nodes and

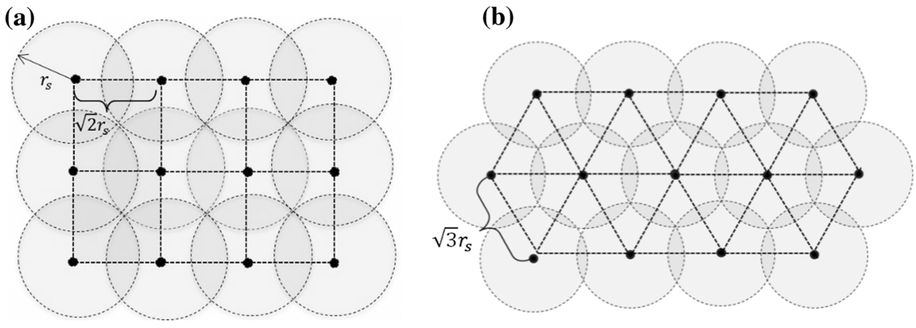

Fig. 1 Illustration of sensor placement. **a** Regular squares. **b** Regular triangles

its distance from the nearest optimal place, determines its own activity rounds. Third, at beginning of each round, the node checks its assigned activation rounds with current round. In the case of positive matching, the node is activated; otherwise, it remains at the inactive state.

4.1 Optimal Sensor Placement

Deterministic node placement aims to locate a minimum number of nodes to satisfy the coverage requirements. Polygon is one of the basic placement patterns, in which, sensor nodes are placed at the polygon's vertices. If all the vertices embedded within the sensor field are covered, then the whole sensor field is said to be fully covered. Figure 1 illustrates how two regular polygons can be used to tile-up the whole sensor field. If sensors are put at the vertices of these regular polygons, the sensor field is fully covered. It is noteworthy, the optimal tessellation using regular squares with side length equal to $\sqrt{2}R_s$ and regular triangles with side length equal to $\sqrt{3}R_s$ achieves the complete area coverage. In CAOP, each node makes its activity decision based on the distance between itself and closest polygon's vertices.

4.2 Sensor Activity Decision

CAOP assumes a randomly deployed network consisting of a large number of sensor nodes. The objective is to optimally schedule sensors activities in order to extend the network lifetime. In CAOP, *delta* is the average distance between sensor nodes, which, can be estimated by Eq. (8):

$$\text{delta} \approx \sqrt{\frac{\text{Area}}{\text{Nodes}_{\text{Number}}}} \tag{8}$$

On the other hand, CAOP works in R-second rounds. In this paper, we define R as a period of time, from the network setup to the time that the deployed network cannot provide adequate coverage. In CAOP, a node can be in one of three states: START, INACTIVE and ACTIVE. The state transition diagram among these three modes is shown in Fig. 2. At the beginning of the first round, all nodes start running CAOP independent of each other to determine activity round. When the decision stage expires, each sensor sets an activation timer with R and goes to the inactive state. At the beginning of each round, all sensor nodes should check their activity round with current round. Any node, whose activity round, is equal with current round will become active; Otherwise, wait for the next timer expiration. For any sensor s at point (x_i, y_i), activity round is defined as follows:

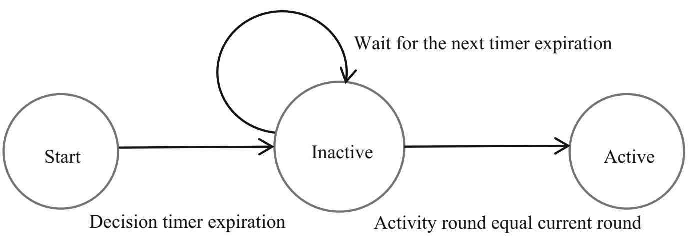

Fig. 2 State transition diagram of operations at each node

$$\mathrm{dx}(s_i) = x_i \bmod \sqrt{2}R_s \tag{9}$$

$$\mathrm{dy}(s) = y_i \bmod \sqrt{2}R_s \tag{10}$$

$$\text{Activity Round}(s_i) = \left\lfloor \frac{\mathrm{dx}(s_i)}{\mathrm{delta}} \right\rfloor + \left(\left\lfloor \frac{\mathrm{dy}(s_i)}{\mathrm{delta}} \right\rfloor \times \left\lceil \frac{\mathrm{r_s}}{\mathrm{delta}} \right\rceil \right) \tag{11}$$

5 Simulation Results and Analysis

In this section, we evaluate the performance of the CAOP via extensive simulations in *ns-2* environment [20]. This simulation considers a 250 × 250 m^2 region, at where, up to 3000 sensors are uniformly randomly distributed and the sensing range of each sensor is 25 m. Considering $\alpha_1 = 0.5$, $\alpha_1 = 0$, $\beta_1 = 0.5$ and $\beta_1 = 0$, in Eq. (3), the coverage ratio of the deployed WSN is shown in Fig. 3.

In an actual environment there are many failure reasons such as the failure of modules (such as communication and sensing module) due to fabrication process problems, environmental effects, atmospheric conditions, battery power depletion and being out of the communication range of the network. Failed nodes may decrease the QoS of WSNs. Hence, it is essential to study the influence of nodes' failure on the coverage of WSNs. For this purpose, we assume that the network experiences a failure with ratio of 0.01 of the available nodes. Then we examine how this failure affects the coverage index, during the time. Figure 4 shows the simulation results. We can see in Fig. 4a that when the number of deployed nodes is 1000, coverage ratio is decreased considerably by this failure ratio. But, as can be seen in Fig. 4b, when the number of nodes is 1500, failure ratio of 0.01 has less effect on the area coverage ratio. This result is expected, since in the case of higher density for the deployed nodes, lack of failed nodes is compensated easily by the other nodes.

As seen in Fig. 4, higher number of deployed nodes hasn't notable impact on the area coverage. Now, we bring other simulation results to examine the impact of the increased number of nodes on the network life time. As shown in Fig. 5, COAP increases life time of

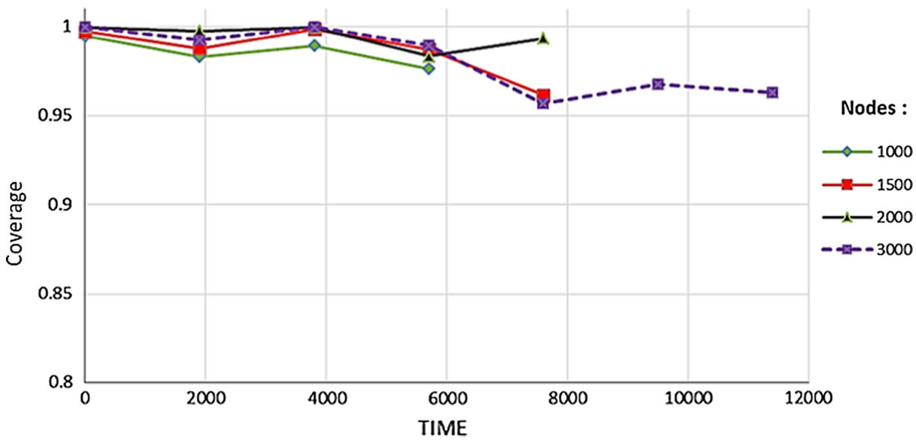

Fig. 3 Coverage rate versus time when nodes = 1000, 1500, 2000 and 3000

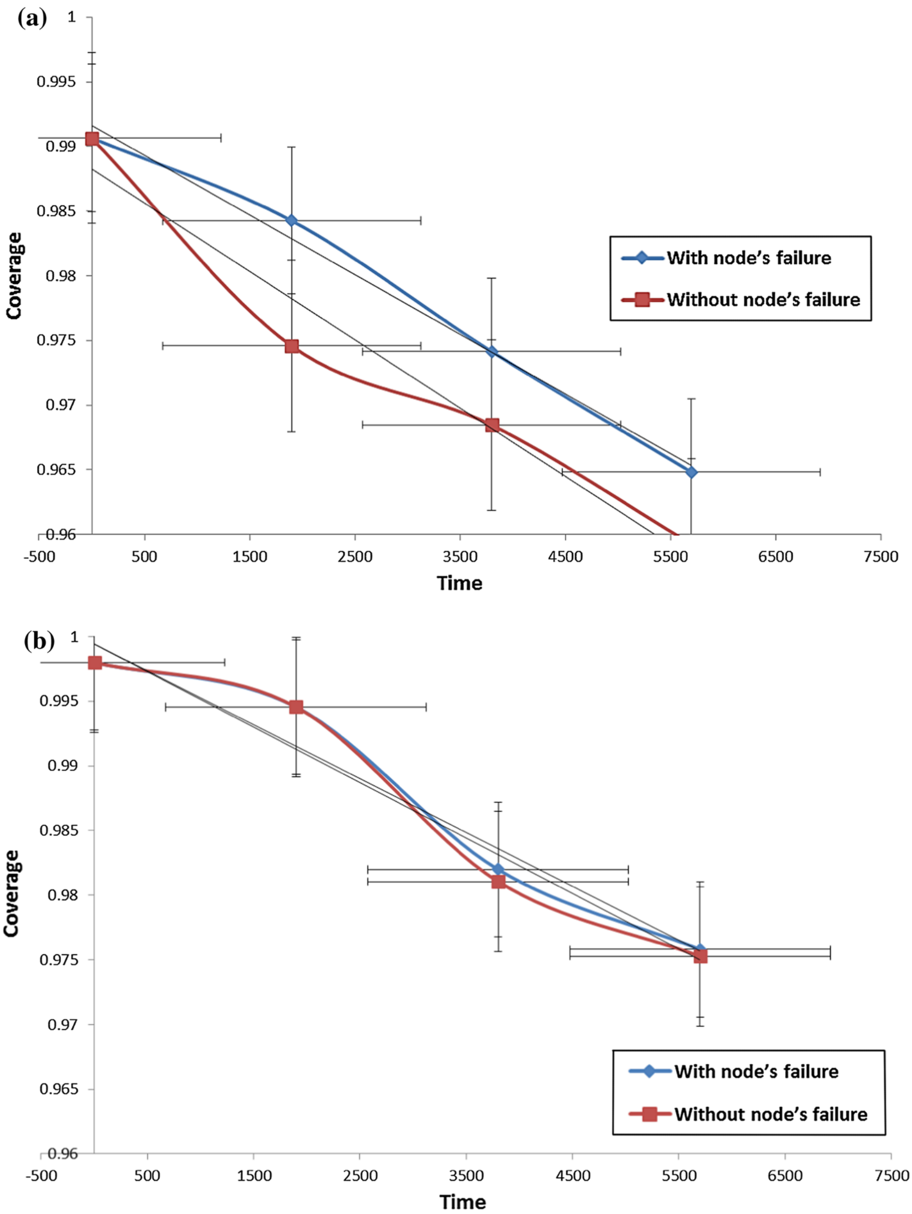

Fig. 4 Effect of node's failure on coverage ratio **a** number of deployed nodes is 1000, **b** number of deployed nodes is 1500

the network by an efficient energy consumption mechanism. Indeed, the proposed approach keeps active only a minimum number of nodes necessary for the area coverage. This means that coverage is cared to be kept always over an acceptable level, but we prevent other nodes from being active. Obviously this can prolong the network life time.

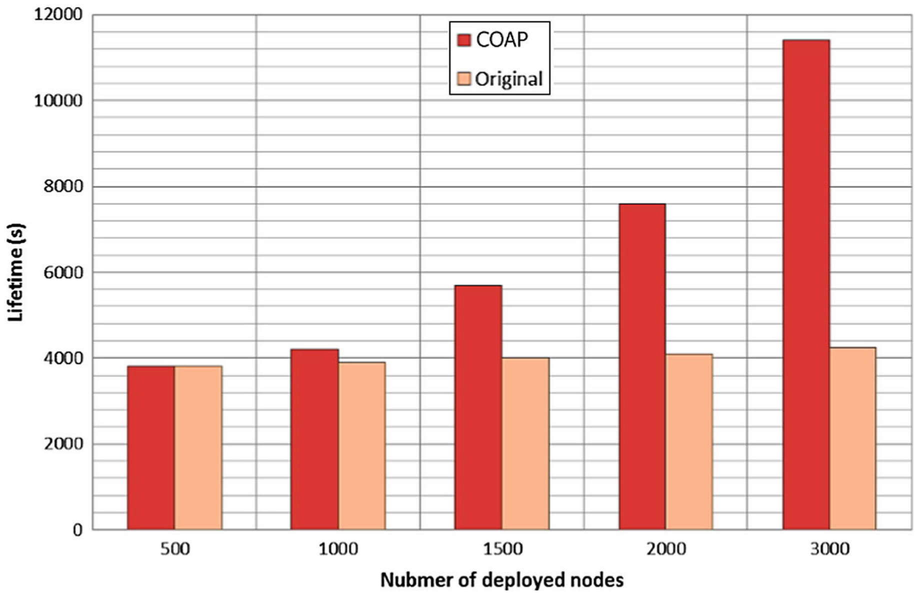

Fig. 5 Network lifetime versus node density

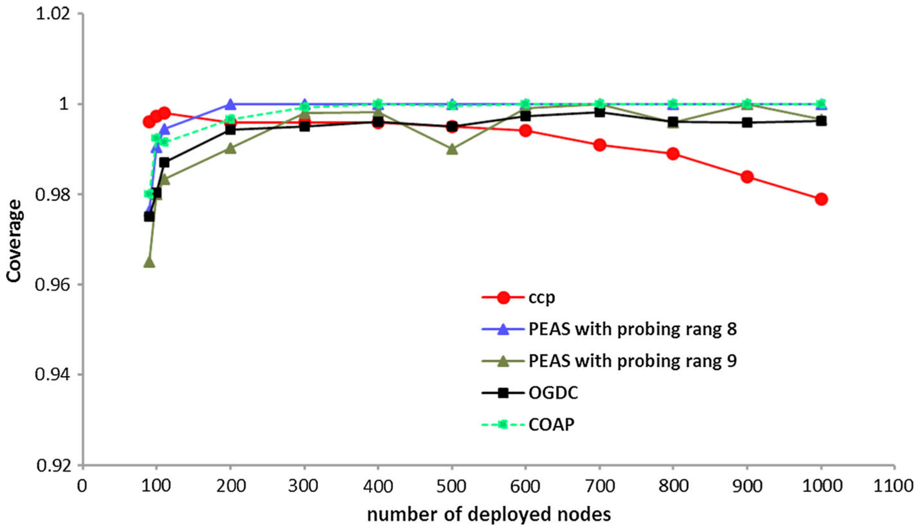

Fig. 6 Coverage rate versus node density

To compare the CAOP's performance with PEAS [3], CCP [3] and OGDC [21], another simulation was conducted in a 50 × 50 m^2 region, in which, up to 1000 sensors are randomly deployed. The sensing range of each sensor is 10 m. The coverage ratio against node density for the probabilistic sensor model is shown in Fig. 6. This figure shows that after an initial transient phase, COAP outperforms other algorithms.

6 Conclusion and Future Work

In this paper, we have proposed a coverage aware scheduling for energy consumption control in WSNs. The basic objective of CAOP is to extend the network lifetime via saving energy. In CAOP, each node makes its activation decision based on the sensor density and its Euclidean distance from the nearest optimal sensor location. By an extensive simulative study we showed that the CAOP outperforms other existing schemes, i.e. PEAS, CCP and OGDC in terms of coverage ratio and network life time. As a direction for the future works, this work will focus on the k-connected coverage problem in the sensor networks and we will try to develop a scheduling algorithm based on the sensor density and location information.

References

1. Rault, T., Bouabdallah, A., & Challa, Y. (2014). Energy efficiency in wireless sensor networks: A top-down survey. *Computer Networks, 67*, 104–122.
2. Rizvi, S., Qureshi, H. K., Ali Khayam, S., Rakocevic, V., & Rajarajan, M. (2012). An energy efficient topology control algorithm for connected area coverage in wireless sensor networks. *Journal of Network and Computer Applications, 35*(2), 597–605.
3. Zhang, Z. L., Li, D., Huang, T. P., & Cui, L. (2013). Leveraging data fusion to improve barrier coverage in wireless sensor networks. *The Journal of China Universities of Posts and Telecommunications (Elsevier), 20*(1), 26–36.
4. Yang, S., Dai, F., Cardei, M., Wu, J., & Patterson, F. (2006). On connected multiple point coverage in wireless sensor networks. *International Journal of Wireless Information Networks, 13*, 289–301.
5. Abdesslem, F. B., Phillips, A., & Henderson T. (2009). Energy efficient mobile sensing with SenseLess. In *The 1st ACM Workshop on Networking, Systems, and Applications for Mobile Handhelds, Barcelona, Spain* (pp. 61–62).
6. Wu, T. T., & Ssu, K. F. (2005). Determining active sensor nodes for complete coverage without location information. *International Journal of Ad Hoc and Ubiquitous Computing, 1*, 38–46.
7. Wang, G., Cao, G., Berman, P., & Porta, T. F. L. (2007). Bidding protocols for deploying mobile sensors. *IEEE Transactions on Mobile Computing, 6*(5), 515–528.
8. Chen, C., Chuang, C. L., Lin, T. S., Lee, C., & Jiang, J. A. (2010). A coverage-guaranteed algorithm to improve network lifetime of wireless sensor networks. *Eurosensor XXIV Conference (Elsevier), 5*, 192–195.
9. Ye, F., Zhong, G., Cheng, J., Lu, S., & Zhang, L. (2003). PEAS: A robust energy conserving protocol for long-lived sensor networks. In *The 23rd international conference on distributed computing systems (ICDCS), USA* (pp. 28–37).
10. Keskin, M. E., Altınel, I. K., Aras, N., & Ersoy, C. (2014). Wireless sensor network lifetime maximization by optimal sensor deployment, activity scheduling, data routing and sink mobility. *Ad Hoc Networks (Elsevier), 17*, 18–36.
11. Alonso, J. M., Voigt, T., & Varshney, A. (2013). Bounds on the lifetime of WSNs. In *IEEE 9th international conference on distributed computing in sensor systems (DCoSS 2013)* (pp. 367–373).
12. Noori, M., & Ardakani, M. (2011). Lifetime analysis of random event-driven clustered wireless sensor networks. *IEEE Transactions on Mobile Computing, 10*(10), 1448–1458.
13. Bai, H., Chen, X., Li, B., & Han, D. (2007). A location-free algorithm of energy-efficient connected coverage for high density wireless sensor networks. *Discrete Event Dynamic Systems (Springer), 17*(1), 1–21.
14. Zhang, L. J., & Wang, H. C. (2011). Energy saving with node sleep and power control mechanisms for wireless sensor networks. *The Journal of China Universities of Posts and Telecommunications (Elsevier), 18*, 49–59.
15. Pan, L., & Li, J. (2010). K-nearest neighbor based missing data estimation algorithm in wireless sensor networks. *Wireless Sensor Network, 2*(2), 115–122.
16. Wang, C. F., & Lee, C. C. (2010). The optimization of sensor relocation in wireless mobile sensor networks. *Computer Communications (Elsevier), 33*, 828–840.

17. Ölveczky, P. C., & Thorvaldsen, S. (2007). Formal modeling and analysis of the OGDC wireless sensor network algorithm in real-time Maude (FMOODS). In *The 9th IFIP WG 6.1 international conference on Formal methods for open object-based distributed systems (Springer)* (pp. 122–140).
18. Banimelhem, O., Mowafi, M., & Aljoby, W. (2013). Genetic algorithm based node deployment in hybrid wireless sensor networks. *Communications and Network, 5*(4), 273–279.
19. Wang, X., & Wang, S. (2011). Hierarchical deployment optimization for wireless sensor networks. *IEEE Transactions on Mobile Computing, 10*(7), 1028–1041.
20. Network simulator. www.isi.edu/nsnam/ns
21. Mahjria, I., Dhraiefa, A., Mabroukia, I., Belghitha, A., & Drirab, K. (2014). The coverage configuration protocol under at-dist localization. In *The 5th international conference on ambient systems, networks and technologies (ANT-2014), Procedia Computer Science* (Vol. 32, pp. 141–148).

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