Decentralized Energy-Conserving and Coverage-Preserving Protocols for Wireless Sensor Networks

Chi-Fu Huang^{*}, Li-Chu Lo^{*}, Yu-Chee Tseng^{**}, and Wen-Tsuen Chen[†]

^{*}Department of Computer Science and Information Engineering
National Chiao-Tung University, Hsin-Chu, 30050, Taiwan

[†]Department of Computer Science
National Tsing-Hua University, Hsin-Chu, 30043, Taiwan

Abstract—The wireless sensor network is an emerging technology that may greatly facilitate human life by providing ubiquitous sensing, computing, and communication capability. However, to maintain sufficient coverage and to achieve long system lifetime are two contradicting factors in designing the topology of a sensor network. In this paper, we propose several decentralized protocols that schedule sensors' active and sleeping periods to prolong the network lifetime while maintain the sensing field sufficiently covered. The proposed protocols are based on a model similar to that of [8], but improve the results of [8] in several senses. First, our approach can significantly reduce the computational complexity incurred, and at the same time achieve better accuracy in determining the coverage of the sensing area. Second, we further enhance the results of [8] by proposing an optimization mechanism to further balance or reduce sensors' energy expenditure.

I. INTRODUCTION

The wireless sensor network is an emerging technology that may greatly facilitate human life. Such environments may have many inexpensive wireless nodes, each capable of collecting, storing, processing environmental information, and communicating with neighboring nodes. In the past, sensors are connected by wire lines. Today, this environment is combined with the novel *ad hoc* networking technology to facilitate inter-sensor communication [5]. Installing and configuring a sensor network thus becomes a simple job. Recently, a lot of research activities have been dedicated to sensor networks, including design of physical and medium access layers [10] and routing and transport protocols [1].

In wireless sensor networks, to maintain sufficient coverage and to achieve long system lifetime are two contradicting factors in topology design. Since sensors are usually powered by batteries, sensors' on-duty time should be properly scheduled to conserve energy. If some nodes share the common sensing region and task, we can turn off some of them to conserve energy and thus extend the lifetime of the network. This issue has been extensively studied recently. Reference [6] proposes a heuristic to select mutually exclusive sets of sensor nodes such

that each set of sensors can provide a complete coverage of the monitored area. Also targeted at turning off some redundant nodes, [9] proposes a probe-based density control algorithm to put some nodes in a sensor-dense area to a doze mode to ensure a long-lived, robust sensing coverage. [4] proposes a coverage-aware self-scheduling scheme based on a probabilistic sensing model. A *Coverage Configuration Protocol (CCP)* that can provide different degrees of coverage and meanwhile maintain communication connectivity is presented in [7]. This work determines the coverage of a network by looking at how intersection points between sensors' sensing ranges are covered by their neighbors, and claims that coverage can imply connectivity as long as sensors' communication ranges are not less than twice their sensing ranges. If the communication ranges are less than twice the sensing ranges, [7] proposes to integrate CCP with SPAN [2] to provide both sensing coverage and communication connectivity.

The work [8] proposes to divide the time axis into rounds with equal duration. Each sensor node randomly generates a reference time in each round. In addition, the whole sensing area is partitioned into grids which are used to evaluate whether the area is sufficiently covered or not. Each sensor has to join the schedule of each grid point covered by itself based on its reference time such that the grid point is covered by at least one sensor at any moment of a round. Then a sensor's on-duty time in each round is the union of schedules for all grid points covered by it. This result has improved over existing results because it allows sensors to be fairly in charge of covering the sensing field in a time-sharing manner. The reference time, which is selected in a random manner, also helps fairly distribute sensors' responsibility (and thus their energy consumption).

This paper proposes several decentralized energy-conserving and coverage-preserving protocols to prolong the network lifetime while maintain the sensing field sufficiently covered. The proposed protocols are based on a model similar to that of [8], but improve the results of [8] in several senses. First, our approach can significantly reduce the computational complexity incurred, and at the same time achieve better accuracy in determining the coverage of the sensing area. Specifically, instead of using grid points as in [8], we utilize

^{*}Y. C. Tseng's research is co-sponsored by the NSC Program for Promoting Academic Excellence of Universities under grant number 93-2752-E-007-001-PAE, by Computer and Communications Research Labs., ITRI, Taiwan, and by Intel Inc.

Fig. 1. The structure of sensors' working cycles.

the result in [7] by calculating sensors' schedules based on the intersection points among their sensing ranges. The result can significantly reduce the computational complexity incurred on each sensor. In addition, the inaccuracy problem caused by gird approximation is completely eliminated. Second, we further enhance the results of [8] by proposing an optimization mechanism to further balance or reduce sensors' energy expenditure. An energy-based scheduling is proposed to intelligently select sensors' reference times. Simulation results are presented to verify the effectiveness of our schemes.

This paper is organized as follows. Section II gives some preliminaries. Our solutions are presented in Section III, while simulation results are presented in Section IV.

II. PRELIMINARIES AND PROBLEM DEFINITION

We are given a set of sensors, $S = \{s_1, s_2, \dots, s_n\}$, in a two-dimensional area A . Each sensor s_i , $i = 1, \dots, n$, knows its own location (x_i, y_i) inside A and has a sensing range of r_i , i.e., it can monitor any point in A that is within a distance of r_i from (x_i, y_i) . Each sensor is able to switch between the *active* mode and the *sleeping* mode. While active, a sensor can conduct sensing tasks and communicate with others at will. While sleeping, a sensor turns off both its sensing and communication components to conserve energy. In addition, each sensor s_i is aware of its current remaining energy, denoted as E_i .

Definition 1: A location in A is said to be *covered* by s_i if it is within s_i 's sensing range and s_i is active.

Definition 2: Two sensors s_i and s_j are said to be *neighbors* if they have non-empty overlapping sensing regions, i.e., $d(s_i, s_j) < r_i + r_j$, where $d(s_i, s_j)$ is the distance between (x_i, y_i) and (x_j, y_j) .

III. 1-COVERAGE-PRESERVING PROTOCOLS

In this section, we first present our basic 1-Coverage-Preserving (1-CP) protocol. Then we enhance our result by presenting an energy-based 1-CP protocol, followed by a complexity analysis.

A. Basic 1-CP Protocol

The proposed protocol is based on a model similar to that in [8]. However, our approach can significantly reduce the

computational complexity incurred on each sensor. The protocol divides the time axis into a sequence of *working cycles*, each of the same length T_{w_cycle} . A working cycle is relatively long, such as a few or tens of minutes. The working cycles of sensors are assumed to be roughly synchronous. Each working cycle consists of two phases, an *initialization phase* of length T_{init} and a *sensing phase* of length T_{sen} . The initialization phase is for sensors to exchange information and use the information to calculate their working schedules for energy conservation purpose. Then in the sensing phase sensors will switch between active and sleeping modes according to their working schedules.

Fig. 1 illustrates the structure of working cycles. During the initialization phase, each sensor s_i has to wake up and broadcast a *HELLO* packet containing the following information: (x_i, y_i) , r_i , and a reference time Ref_i , where Ref_i is a value generated from some random process. Based on the HELLO packets received from neighbors, s_i can calculate its own working schedule in the sensing phase. To avoid possible collisions, a random backoff should be taken before sending HELLO. The sensing phase is divided into r rounds, each of the same duration T_{rnd} , i.e., $T_{sen} = r \times T_{rnd}$. In each round, s_i will have a regular active and sleeping pattern as specified below.

Intuitively, sensors will take the responsibility of sensing the environment cooperatively with its neighbors in a time-sharing manner. Let us consider one round in the sensing phase of a working cycle. We denote its duration by $[0, T_{rnd})$. We will choose two values, $Front_i$ and $Back_i$, for sensor s_i , and schedule s_i to be active from $[(Ref_i - Front_i) \bmod T_{rnd}]$ to $[(Ref_i + Back_i) \bmod T_{rnd}]$, and to go to sleep for the rest of the round. Note that here we treat the duration of a round as circular time, i.e., time T_{rnd} in a round actually wraps around to time 0 of the round.

Next, we present a basic method for selecting Ref_i , $Front_i$, and $Back_i$ for sensor s_i . The method is a modification of the scheme in [8]. First, s_i generates a reference time Ref_i which is uniformly distributed among $[0, T_{rnd})$. Then, from the HELLO packets received from s_i 's neighbors, s_i should maintain a neighbor table which contains all its neighbors' locations, sensing ranges, and reference times. The parameters $Front_i$ and $Back_i$ should be carefully selected to ensure that

Fig. 2. (a) a 5-sensor example, (b) schedules of s_1 , s_2 , and s_3 for intersection point p , and (c) the integrated schedule of s_1 .

the sensing area is sufficiently covered. To achieve this goal, we utilize a theorem stated in [3], which claims that, if all intersection points between any two sensors' sensing ranges and between any sensor's sensing range and the boundary of A are sufficiently covered, the target area A is sufficiently covered. This result is also used in [7] to guarantee the coverage of a sensor network. More specifically, for each intersection point, we have to schedule at least one sensor to be on-duty at any moment among all sensors which cover the point. This would lead to a more efficient distributed protocol than that in [8] (refer to the analysis in Section III-C).

To calculate $Front_i$ and $Back_i$, let the set of intersection points inside s_i 's sensing area be P . For each intersection point $p \in P$, s_i has to calculate two values, $Front_{p,i}$ and $Back_{p,i}$, as follows. Let $C(p)$ be the set of sensors that cover point p (including s_i). Then s_i sorts the reference times of all these sensors in $C(p)$ into a list L_p in an ascending order, and derives that:

$$Front_{p,i} = [(Ref_i - prev(Ref_i)) \bmod T_{rnd}] / 2 \quad (1)$$

$$Back_{p,i} = [(next(Ref_i) - Ref_i) \bmod T_{rnd}] / 2, \quad (2)$$

where $prev(Ref_i)$ and $next(Ref_i)$ are the reference times before and after Ref_i in the list L_p , respectively. Note that here we consider L_p as a circular list, i.e., the one next to the last item in L_p is the first item in L_p , and vice versa. Intuitively, Eq. (1) and Eq. (2) are designed to have sensors in L_p cooperatively cover point p in a time-division manner. For two consecutive reference times in L_p , the corresponding two sensors will divide their responsibility at the middle point of their reference times, such that one covers p before the middle point, and the other does after the middle point. This is formally stated in the following lemma.

Lemma 1: For any intersection point p , if each sensor $s_i \in C(p)$ is active in the duration $[Ref_i - Front_{p,i}, Ref_i + Back_{p,i}]$ (in the circular sense), then p is covered by exactly one sensor in each round.

Fig. 2(a) shows an example. Intersection point p is covered by sensors $C(p) = \{s_1, s_2, s_3\}$. Let T_{rnd} be 20, and the reference times of s_1 , s_2 , and s_3 be 2, 9, and 11, respectively. So we have $Front_{p,1} = [(2 - 11) \bmod 20] / 2 = 5.5$, and $Back_{p,1} = [(9 - 2) \bmod 20] / 2 = 3.5$. Similarly, $Front_{p,2} = 3.5$, $Back_{p,2} = 1$, $Front_{p,3} = 1$, and $Back_{p,3} = 5.5$. The

schedules of s_1 , s_2 , and s_3 to cover p are shown in Fig. 2(b). As can be seen, p is covered by exactly one sensor at all time in a round.

It is not hard to see that the above schedules may result in inconsistent active time, because for each point p covered by s_i , it has an independent schedule. To ensure that each intersection point is covered, the active period of sensor s_i should be the union of schedules obtained from all intersection points under s_i 's coverage. So we define:

$$Front_i = \max_{p \in P} \{Front_{p,i}\} \quad (3)$$

$$Back_i = \max_{p \in P} \{Back_{p,i}\}. \quad (4)$$

Theorem 1: If each sensor s_i is active in the duration $[Ref_i - Front_i, Ref_i + Back_i]$ of each round (in the circular sense), then the whole sensor network is covered in each round.

For example, if in Fig. 2(a) the reference times of s_4 and s_5 are 16 and 18, respectively, the integrated schedule of sensor s_1 will be as shown in Fig. 2(c).

B. Energy-Based 1-CP Protocol

The above basic scheduling does not consider the individual status of sensors – reference times are randomly selected, so sensors equally divide their responsibility to cover the sensing field. Below, we try to utilize sensors' remaining energies to balance their energy consumption and prolong network lifetime. Note that this requires each sensor s_i to broadcast its remaining energy E_i in the HELLO packet.

Reference times are chosen differently. Observe that for each intersection point p , the interval between two adjacent reference times in L_p will affect the corresponding sensors' on-duty times in a round. Therefore, the reference times of sensors with more energies should be placed more sparsely in the duration of a round than those with less energies. To achieve this goal, each round is logically divided into two zones with different lengths, $[0, \frac{3T_{rnd}}{4})$ and $[\frac{3T_{rnd}}{4}, T_{rnd})$. Sensors with more energies should randomly choose their reference times from the larger zone, while sensors with less remaining energies should choose from the smaller zone. The criteria to determine sensors' remaining energies may be based on some agreement, such as a threshold. Alternatively,

a node finding its remaining energy ranked top 50% among its neighbors can choose from the larger zone; otherwise, it chooses from the smaller zone. Note that lengths of zones are also be tuned.

Parameters $Front_i$ and $Back_i$ of sensor s_i are also chosen based on E_i . For any point p , we modify Eq. (1) and Eq. (2) according to the ratios of sensors' remaining energies as follows:

$$Front_{p,i} = [(Ref_i - prev(Ref_i)) \bmod T_{rnd}] \times \frac{E_i}{E_i + E_{i'}} \quad (5)$$

$$Back_{p,i} = [(next(Ref_i) - Ref_i) \bmod T_{rnd}] \times \frac{E_i}{E_i + E_{i''}}, \quad (6)$$

where i' and i'' are the sensors in $C(p)$ whose reference times are before and after Ref_i (i.e., $prev(Ref_i)$ and $next(Ref_i)$) in L_p , respectively. The definitions of $Front_i$ and $Back_i$ are unchanged, and the rest of the procedure is the same.

C. Complexity Analysis

The computational complexity of the proposed protocol is analyzed below. To calculate its working schedule, a sensor first looks at its neighbor table and extracts reference times of its neighbors. Suppose that a node has at most d neighbors. Sorting these reference times takes time $O(d \log d)$. The maximum number of intersection points covered by a sensor is $O(d^2)$. For each intersection point, a sensor has to find out which nodes cover the point, which takes time $O(d)$. So, the calculation of working schedule for all intersection points takes time $O(d^3)$. Finally, calculating Eq. (3) and Eq. (4) takes time $O(d^2)$. Therefore, a complexity of $O(d^3)$ is incurred on each node to decide its working schedule. Note that the energy-based scheduling has the same complexity as the basic scheme.

Next, we compare our scheme with that in [8], which takes a grid approximation approach. The complexity of [8] is related to the grid size of the entire region (while our protocol is independent of the grid size). Suppose that each grid has a width of g and each sensor's sensing range is r , then there are approximately $\frac{\pi r^2}{g^2}$ grids to be taken care of by a sensor. As a result, it takes time $O(d \frac{\pi r^2}{g^2})$ for a sensor to decide its working schedule.

IV. SIMULATION RESULTS

We have developed a simulator to compare the performance of the proposed energy-conserving protocols. The simulation environment is a 100×100 square area, on which 150 sensors are randomly generated. Each sensor has a sensing range of 25. In addition, each sensor will be rescheduled every 5 rounds, i.e., a cycle includes 5 rounds. To set up sensors' initial energies, we allow a sensor to be able to remain active from 1 to 50 complete rounds in a randomly selected manner.

We compare our basic protocol with the energy-based protocol. There are two kinds of performance metrics: the ratio of alive nodes and the ratio of covered area. The results are shown in Fig. 3 and Fig. 4. As can be seen in Fig. 3, adopting our basic protocol can prolong sensors' lifetime. In addition, our energy-based protocol further outperforms the basic protocol. Similar effects are also reflected on the ratio

Fig. 3. The ratio of alive nodes.

Fig. 4. The ratio of covered area.

of covered area, as shown in Fig. 4. The energy-based protocol can keep almost 100% coverage until about 60 rounds while the curve of the basic protocol fluctuates. This is because that in our basic protocol, due to lack of energy balance, some nodes may deplete their energies more quickly, causing an uncovered area.

REFERENCES

- [1] D. Braginsky and D. Estrin. Rumor routing algorithm for sensor networks. In *ACM Int'l Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2002.
- [2] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *ACM/Kluwer Wireless Networks*, 8(5):481–494, Sep. 2002.
- [3] P. Hall. *Introduction to the Theory of Coverage Processes*. Wiley, New York, 1988.
- [4] J. Lu and T. Suda. Coverage-aware self-scheduling in sensor networks. In *IEEE Computer Communications Workshop (CCW)*, 2003.
- [5] G. J. Pottie and W. J. Kaiser. Wireless integrated network sensors. *Commun. ACM*, 43(5):51–58, May 2000.
- [6] S. Slijepcevic and M. Potkonjak. Power efficient organization of wireless sensor networks. In *IEEE Int'l Conf. on Communications (ICC)*, pages 472–476, 2001.
- [7] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill. Integrated coverage and connectivity configuration in wireless sensor networks. In *ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys)*, pages 28–39, 2003.
- [8] T. Yan, T. He, and J. A. Stankovic. Differentiated surveillance for sensor networks. In *ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys)*, pages 51–62, 2003.
- [9] F. Ye, G. Zhong, S. Lu, and L. Zhang. PEAS: A robust energy conserving protocol for long-lived sensor networks. In *Int'l Conf. on Distributed Computing Systems (ICDCS)*, 2003.
- [10] W. Ye, J. Heidemann, and D. Estrin. An energy-efficient MAC protocol for wireless sensor networks. In *IEEE INFOCOM*, pages 1567–1576, 2002.