A Distributed Probabilistic-Coverage Node Scheduling Scheme for Large Wireless Sensor Networks

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Abstract—**In wireless sensor networks, coverage configuration is an important issue which can prolong the system lifetime significantly. Most of current literatures are based on physical coverage, i.e. deterministic detection model, which is inconsistent with the realistic application of wireless sensor networks. A distributed probabilistic coverage configuration protocol (DPCCP) is proposed in this paper. It adopts Neyman-Peason probabilistic detection model to decide whether nodes can be off or not. Our DPCCP guarantees that the system detection probability is maintained after turning off lots of unnecessary nodes. We extend LEACH by embedding DPCCP into LEACH (namely LEACHE) seamlessly without any modification of the original workflow. Simulation results show that DPCCP can effectively reduce the number of active sensor nodes, and LEACHE outperforms LEACH in terms of system lifetime and energy efficiency.**

Keywords-distributed; probabilistic coverage; wireless sonser networks

I. INTRODUCTION

Recently, wireless sensor network (WSN) has been widely used in the fields of military affairs, intelligent family, environment surveillance and commercial management and so on [1].

Coverage configuration has become an important issue in the research of energy-constrained WSN [4]. Generally speaking, the coverage problem in WSN can be classified into there kinds: physical coverage, information coverage and probabilistic coverage. The definition of physical coverage presented in [5] is that a point is said to be covered if its Euclidean distance to a sensor is within the sensing radius of the sensor. Many configuration mechanisms are proposed based on this deterministic detection model, such as [2, 6, 7]. However, under the deterministic detection model, each sensor works and makes decision independently without considering the cooperation with neighbors, which is not consistent with the idealistic application of WSN and still waste system energy on certain level. Information coverage is proposed firstly in [5] via estimation theory. The cooperation of nodes is accomplished by fusing the measurements of sensors in a signal source at a particular position. The fusion center can make correct estimation by the cooperation of a set of nodes, while it is impossible to do by any individual sensor. A scheduling scheme for point information coverage is described in [8], and an improvement of information coverage configuration mechanism is proposed in [12].

Probabilistic coverage adopts probabilistic detection models. The non-deterministic detection model taken by probabilistic coverage incorporates the signal decay function into detection models. Obviously, it is more realistic than deterministic detection model. Several probabilistic coverage configuration algorithms have been proposed. The Co-Grid coverage maintenance protocol [10] organizes the network into fusion groups located on overlapping virtual grids. Through effective coordination among neighboring fusion groups, Co-Grid can achieve comparable number of active nodes as the centralized algorithm. But the drawbacks of this protocol are high communication cost for detection and centralized algorithm which is inapplicable in realistic application. In [9], a distributed Probabilistic Coverage Algorithm (PCA) based on probabilistic coverage is proposed. But PCA only provide a distributed algorithm to evaluate the degree of confidence of detection probabilistic for randomly deployed sensor network without configuring the network. Additionally, both [9, 10] do not integrate the research results with specifically routing protocols.

In our work, we propose a distributed probabilistic coverage configuration protocol (DPCCP) based on Neyman-Peason probabilistic detection model similar to [10, 11]. The contributions of this paper are as follows. Firstly, we analyze critical parameters in signal decay model which significantly influence the detection probability. Secondly, we present a distributed node scheduling scheme based on probabilistic coverage for randomly deployed WSN which can configure the operation mode of sensor nodes. The presented scheduling scheme can arrange a mass of redundant sensor nodes to turn off with the guarantee of the original network sensing coverage. Thirdly, we extend the classical LEACH protocol [13] by inserting the self-scheduling phase of our scheme before LEACH's cluster set-up phase without any modification of the original LEACH protocol, namely LEACH-Extension

(LEACHE), and evaluate our algorithm by comparing LEACHE with the original LEACH protocol.

The rest of our paper is organized as follows. In section 2, we present the problem formulation, followed by details of our distributed probabilistic coverage configuration protocol (DPCCP) in section 3. Then, simulation results are introduced in section 4. Section 5 makes a conclusion.

II. PROBLEM FORMULATION

A. Probabilistic detection model and analyses

We assume that N sensors are randomly deployed in the region of interest (ROI), with locations (x_i, y_i), $i = 1,2,\ldots,N$, the sensor i can make a measurement from a target by following equation:

$$a_i = \frac{\theta}{d_i^{\alpha}} \qquad i = 1,2,\ldots,N \tag{1}$$

Where θ is the signal strength emitted by the target, α is the signal decay exponent and takes values between 1 and 2, d_i is the distance from the target to the sensor i, i.e., $d_i = \sqrt{(x_i - x_t)^2 + (y_i - y_t)^2}$.

We assume that n_i is the noise at sensor i and follows a Caussian distribution with zero mean, i.e. $n_i \sim (0,\sigma)$. For sensor i, the binary hypothesis testing problem is:

$$H_1:\ z_i = a_i + n_i \qquad H_0:\ z_i = n_i \tag{2}$$

Because n_i is modeled as a Gaussian distribution, equation (2) can be described as follows [10]:

$$H_1:\ p(z_i|H_1) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(z_i - a_i)^2}{2\sigma^2}\right) \tag{3}$$
$$H_0:\ p(z_i|H_0) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{z_i^2}{2\sigma^2}\right)$$

Assume that all the sensors use the same detection threshold τ to make a decision, the relationship between threshold and the false alarm rate is given by [11]:

$$P_{f_i} = \int_{\tau}^{\infty} p(z_i|H_0)dz_i = Q\left(\frac{\tau}{\sigma}\right) \tag{4}$$

$$\tau = \sigma\ Q^{-1}(P_{f_i}) \tag{5}$$

Where $Q(\bullet)$ is the complementary distribution function of the standard Gaussian, i.e.:

$$Q(x) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt \tag{6}$$

The detection probability in location (x_t, y_t) by sensor i is:

$$P_{Di} = \int_{\tau}^{\infty} p(z_i|H_1)dz_i = Q\left(\frac{\tau - a_i}{\sigma}\right) \tag{7}$$

According to (7), we can see there are some critical parameters in signal decay model which highly affect detection probability.

The relationship of detection probability P_{Di}, signal decay exponent α and distance d_i is shown in Figure 1. Obviously, P_{Di} decrease dramatically with the increase of α and d_i.

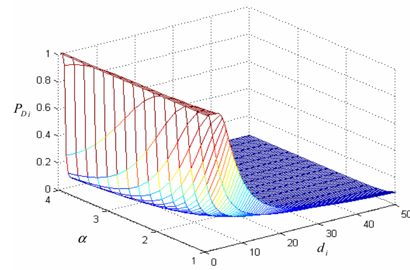


Figure 1. The relationship of P_{D_i}, α and d_i when $\theta = 15$, $P_{f_i} = 0.05$ and $\sigma = 1$.

In WSN, many sensors are deployed in sensing field to detect the interested events. Usually, a point in sensing field can be sensed by more than one sensor. The overall system detection probability by all the sensors motivated by [9] is:

$$P_D = 1 - \prod_{i=1}^{N}(1 - P_{Di}) \tag{8}$$

It means that if an individual sensor can detect an interested event with the detection probability P_{Di}, when several sensors perform the same task at the same time, the overall detection probability P_D on detecting the same event will be no less than the single detection probability P_{Di}. The curve of detection probabilities and more details are given in [9].

B. Parameters of DPCCP

Because of the large scale and high density of the network, it is impossible to consider all the nodes' contributions when calculate the detection probability on point (x_t, y_t) by equation (8). Here we make three definitions to simplify equation (8).

Definition 1 (Lower-Limit sensing radius R_l). Assume that the minimum system detection probability which can guarantee the desired performance of the network is TH_l. Then R_l for a sensor is defined as:

$$R_l = \left[\frac{\theta}{\sigma Q^{-1}(1 - TH_l) + \tau}\right]^{1/\alpha} \tag{9}$$

R_l is the maximum sensing radius with which an individual sensor can still detect an event with a detection probability higher than TH_l. See more details in Appendix A.

Definition 2 (TH_l-Probabilistic Coverage). A point (x, y) is said to be TH_l-covered if there exists a set of sensors which make the system detection probability P_D on this point satisfies $P_D \ge TH_l$. A region is said to be completely TH_l -covered if any point in the region is TH_l -covered.

This definition is motivated by the definition of information coverage in paper [5]. Obviously, a point (x, y) point must be TH_l -covered if the Euclidean distance between this point and sensor i is no more than R_l .

Definition 3 (Upper-Limit sensing radius R_u). Assume when a sensor's detection probability for an event is smaller than a predefined threshold TH_u , its contribution to the system detection probability for that event will be neglected. Then R_u is defined as:

$$R_u = \left[\frac{\theta}{\tau - \sigma Q^{-1}(TH_u)} \right]^{1/\alpha} \tag{10}$$

If the Euclidean distance between a point (x, y) and sensor i is more than R_u , then the influence of node i on the detection of point (x, y) will be neglected. See more details in Appendix B.

Based on the definitions above, our algorithm is proposed with the following assumptions.

Assumption 1. Each sensor knows its own position.

Assumption 2. $R_c \ge R_u$, where R_c is the communication range. It is means that connectivity can be guaranteed in our work.

III. DISTRIBUTED PROBABILISTIC COVERAGE CONFIGURATION PROTOCOL (DPCCP)

In this section, our distributed probabilistic coverage configuration protocol (DPCCP) will be presented. This protocol bases on Neyman-Peason probabilistic detection model and makes use of the characteristics of Voronoi diagram to schedule nodes whether to keep active or go to sleep.

A. Voronoi diagram

A survey of Voronoi diagram is presented in [3]. In our paper, the concept of Voronoi diagram is used to divide the ROI into small cells. Suppose N sensors are randomly arranged in a two dimensional plane, then the plane can be divided in to N convex polygons. Each polygon only contains a sensor node and any point in this convex polygon has the minimum distance to the sensor comparing with the distances to other sensors in the network. In our work, we denote the convex polygon containing node i as $CP(i)$.

According to the definition of Voronoi diagram, a point (x, y) in a convex polygon i should satisfy the following inequality:

$$\sqrt{(x-x_i)^2 + (y-y_i)^2} \le \sqrt{(x-x_k)^2 + (y-y_k)^2}, k = 1,2,\ldots,N \tag{11}$$

The equal sign is true when $i = k$.

B. Node self-scheduling scheme

Our protocol is designed for large scale and high dense network, so some reasonable assumptions can be made. If sensor i is on-duty, $CP(i)$ is TH_l -covered. If any point in $CP(i)$ satisfies TH_l-probabilistic coverage, the node i should be off. Whereas, if more than one point in $CP(i)$ does not satisfy TH_l-probabilistic coverage, then the sensor i should be on.

Actually, it is difficult to calculate the probability of every point in $CP(i)$ due to a high cost of computation. To simplify our algorithm, we make a similar assumption with [10]. Assume the target only appears at the vertices and the sensor position of $CP(i)$, and these points are referred as sample points. If these sample points are all TH_l -covered, then the region of $CP(i)$ is TH_l -covered. This assumption is reasonable in high dense WSN.

The pseudo code for DPCCP at each node is given below:

The node self-scheduling scheme of sensor i :

Begin

Input:

$P_f =$ False alarm probability

$TH_l =$ Threshold of system detection probability

$TH_u =$ Threshold of unnecessary detection probability

$(x_j, y_j) =$ Coordination of other nodes can be heard by node i , where $j = 1,2,\ldots,M$

Notations:

$P_{f_i} = P_f \qquad i = 1,2,\ldots,N$

$Ver_k^i =$ Position of the k th vertex of node i , where $k = 1,2,\ldots,K$

$Ver_{K+1}^i =$ Position of node i

$P_D(x_t, y_t) =$ System detection probability on point (x_t, y_t)

d_{ij} = Distance between node i and node j

$state(i) =$ State flag of node i ,"0" is the initial state, "1" is the on-duty state and "2" is the off-duty state

$S_l^i =$ Set of nodes which have the distances $d_{ij} \le R_l$ and $state(j) = 1$, where $j = 1,2,\ldots,M$

$S_u^i =$ Set of nodes which have the distances $d_{ij} \le R_u$ and $state(j) = 1$, where $j = 1,2,\ldots,M$

Process:

set $state(i) = 0$

if $S_l^i \ne \Phi$ **then** $\qquad state(i) = 2$

elseif $S_u^i = \Phi$ **then** $\quad state(i) = 1$

elseif $S_l^i = \Phi$ and $S_u^i \neq \Phi$ **then**

for $k = 1:(K+1)$ **do**

for $m = 1:M$ **do**

select one node j from S_u^i which has not been selected before

calculate $P_D(Ver_k^i)$ by considering the affection of j

if $P_D(Ver_k^i) \geq TH_l$ **then** break **end if**

end for

end for

if all the $P_D(Ver_k^i) \geq TH_l \quad k = 1,2,\ldots,K+1$ **then**

$state(i) = 2$

else $state(i) = 1$

end if

end if

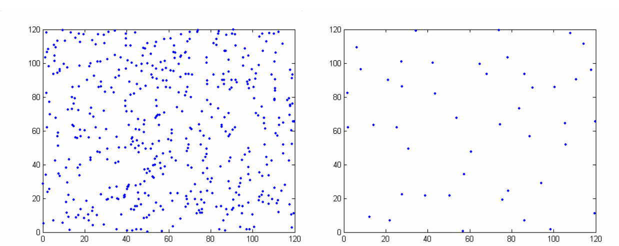
End

From the pseudo code, we can see if there is at least one on-duty node in the sensor i 's range of lower limit R_l, sensor i should works on off-duty state. If none of on-duty node in the sensor i 's range of upper limit R_u, sensor i should works on on-duty state. Except for two situations before, the system detection probability of $CP(i)$ should be calculated using equation (8), and sensor node should determine its operation mode through our decision rule.

IV. SIMULATION RESULTS

In this section, performance of our node self-scheduling scheme will be evaluated and then the extension of LEACH will be made in the simulation.

Figure 2 shows the distributions of on-duty sensors in terms of (a) distribution without coverage configuration and (b) distribution after DPCCP. Both of them are under the same initial topology. Comparing with figures (a) and (b), the simulation results show that DPCCP can effectively turns off redundant nodes with the guarantee of the original network sensing coverage.



(a) (b)

Figure 2. Distribution of on-duty nodes when $N = 500$, $Area = 120m \times 120m$, $TH_l = 0.90$, $P_{f_i} = 0.05$, $TH_u = 0.06$, $\theta = 15$, $\alpha = 1$ and $\sigma = 1$.

Next, we will extend LEACH to evaluate our algorithm by comparing LEACH-Extension with the original protocol.

LEACH (Low-Energy Adaptive Clustering Hierarchy) [13] is a classical distributed cluster-based routing protocol, and many other cluster-based routings are motivated by LEACH. In LEACH, cluster heads randomly rotate in order to balance the network energy dissipation. It works in round. Each round can be divided into two stages, cluster setup stage and steady communication stage. In cluster setup stage, cluster heads are randomly produced, nodes in the network organize themselves into certain groups called clusters, and the cluster head as the control node in each cluster takes charge of the communication between the base station and non-cluster-head nodes. In steady communication stage, using a TDMA schedule for data transfer, each cluster head creates a TDMA schedule that allocates timeslots for each cluster member, then gathers and fuses data from cluster members and transfers data to the base station.

We extend LEACH by inserting the self-scheduling phase of our scheme before the LEACH cluster set-up phase without any modification of original workflow, namely LEACH-Extension (LEACHE). In LEACHE, the performance can be organized into rounds. The coverage configuration protocol DPCCP is inserted directly before the sensing phase. It is implied that at the beginning of each round in LEACHE, nodes determine whether they should keep active or not by themselves through DPCCP.

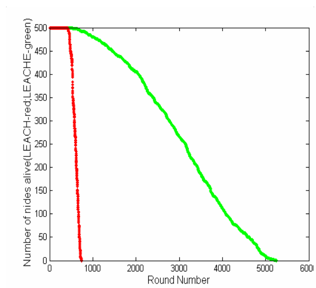


Figure 3. Number of nodes alive over round

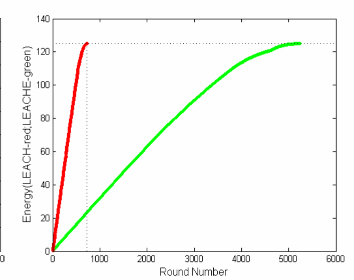


Figure 4. Overall energy dissipation curve

The followings are the simulation parameters: $N = 500$, $Area = 120m \times 120m$, $TH_l = 0.90$, $P_{f_i} = 0.05$, $TH_u = 0.06$, $\theta = 15$, $\alpha = 1$, $\sigma = 1$, the initial energy of each node $E_0 = 0.25J$ and the position of base station $(x_b, y_b) = (60m, 150m)$. As shown in figure 3, LEACHE outperforms LEACH especially in the round number of last node die. The round number of first node die in LEACH is about 410 rounds while about 510 rounds in LEACHE. The round number of last node die in LEACHE is about 5240 rounds which is about 7 times as LEACH's 740 rounds. Figure 4 shows the overall energy dissipation curves of LEACH and LEACHE. It is clear that the change of network energy dissipation in LEACHE is slower then the one in LEACH with the round increasing. When the overall energy is dissipated in LEACH, only less than 20% overall energy is consumed in LEACHE. The outstanding performance of LEACHE on energy dissipation is due to the node self-scheduling scheme proposed above. Using this scheme, with a predefined system detection probability and sensor node's false alarm rate, a lot of redundant sensor nodes can be turned off to save energy in each round.

V. CONCLUSIONS

In this paper, we proposed a node self-scheduling scheme based on probabilistic detection model. This distributed coverage configuration algorithm can prolong the network lifetime and improve energy efficient effectively in large scale high dense WSN. The Neyman-Peason probabilistic detection model is adopted by DPCCP. In DPCCP, due to the cooperation of nodes, lots of redundant sensor nodes can be turned off with the guarantee of the original network sensing coverage. The extension of LEACH is introduced too, which further enhances the performance of original one by embedding DPCCP into LEACH without any modification of original workflow.

APPENDIX

A. Lower-Limit sensing radius R_l

According to (7), if there is only an individual sensor i performance sensing task on point (x_t, y_t) in the network. The threshold of system detection probability is TH_l where $TH_l > 0.5$. So the system detection probability should satisfy the following inequality.

$$P_D = P_{Di} = Q\left(\frac{\tau - a_i}{\sigma}\right) \geq TH_l$$

According to (6), $Q(\bullet)$ is a single decrease function, and $Q(\bullet)$ satisfies the equation, i.e., $Q(-x) = 1 - Q(x)$ And $TH_l > 0.5 \Rightarrow \frac{\tau - a_i}{\sigma} < 0$

Therefore,

$$\Rightarrow 1 - Q\left(\frac{a_i - \tau}{\sigma}\right) \geq TH_l \Rightarrow \frac{a_i - \tau}{\sigma} \geq Q^{-1}(1 - TH_l)$$
$$\Rightarrow a_i \geq \sigma Q^{-1}(1 - TH_l) + \tau$$

Considering (1), then

$$\Rightarrow d_i \leq R_l \qquad \text{Where } R_l = \left[\frac{\theta}{\sigma Q^{-1}(1 - TH_l) + \tau}\right]^{1/\alpha}$$

The deduction of appendix A is complete.

B. Upper-Limit sensing radius R_u

We also assume there is only an individual sensor i performance sensing task on point (x_t, y_t) in the network. According to (8), if the detection probability of sensor i on point (x_t, y_t) is smaller than TH_u where $P_{f\,i} < TH_u < 0.5$, the contribution to the system detection probability of sensor i on this point can be neglected. Then the sensor i detection probability can be given as:

$$P_{Di} = Q\left(\frac{\tau - a_i}{\sigma}\right) \leq TH_u$$

Similar as appendix A, $Q(\bullet)$ is a single decrease function. $Q(\bullet)$ satisfies the equation, i.e., $Q(-x) = 1 - Q(x)$ And $P_{f\,i} < TH_u < 0.5 \Rightarrow \frac{\tau - a_i}{\sigma} > 0$

Therefore,

$$\Rightarrow \frac{\tau - a_i}{\sigma} \geq Q^{-1}(TH_u) \Rightarrow a_i \leq \tau - \sigma Q^{-1}(TH_l)$$

Considering (1), then

$$\Rightarrow d_i \geq R_u \qquad \text{Where } R_u = \left[\frac{\theta}{\tau - \sigma Q^{-1}(TH_u)}\right]^{1/\alpha}$$

The deduction of appendix B is complete.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey", IEEE Computer Networks, vol. 38, 2002, pp. 393–422.

[2] D. Tian, N. Georganas, "A coverage-preserving node scheduling scheme for large wireless sensor networks", Proc. of the 1st ACM Int'l Workshop on Wireless Sensor Networks and Applications, pp. 32-41, 2002.

[3] F. Aurenhammer, "Voronoi diagrams—A survey of a fundamental geometric data structure", ACM Computing Surveys, 1991,23(3): 345-405.

[4] M. Cardei and J. Wu. "Energy-efficient coverage problems in wireless adhoc sensor networks", Journal of Computer Communications on Sensor Networks. 2005.

[5] B. Wang, W. Wang, V. Srinivasan, K.C. Chua. "Information coverage for wireless sensor networks", IEEE COMMUNICATIONS LETTERS, VOL. 9, NO. 11, NOVEMBER 2005, pp.967-969.

[6] M. Cardei, M. Thai, Y. Li, and W. Wu, "Energy-Efficient Target Coverage in Wireless Sensor", Networks, IEEE INFOCOM 2005, Mar. 2005. 3.

[7] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, C. Gill. "Integrated coverage and connectivity configuration in wireless sensor networks". Proc. of the ACM Int'l Conf. on Embedded Networked Sensor Systems (SenSys). New York: ACM Press, 2003. 28-39.

[8] B. Wang, K.C. Chua, V. Srinivasan, and W. Wang, "Scheduling sensor activity for point information coverage in wireless sensor networks," in Proceedings of WiOpt, 2006.

[9] N Ahmed, S Kanhere, S Jha, "Probabilistic coverage in wireless sensor networks", Proceedings of the 30th conference on local computer networks, IEEE, USA, 2005, pp. 672 – 679.

[10] G.L. Xing, C.Y. Lu, R. Pless, J.A. O'Sullian. "Co-Grid: an Efficient Coverage Maintenance Protocol for Distributed Sensor Networks", IPSN'04, Berkeley, California, USA, pp.414-423.

[11] R. Niu, P.K. Varshney, M.H. Moore, D. Klamer, "Decision fusion in a wireless sensor network with a large number of sensors", in: Proceedings of the 7th International Conference on Information Fusion, Stockholm, Sweden, June 2004.

[12] H. Bai, X. Chen, Y.C. Ho, X. Guan. "Information Coverage Configuration with Energy Preservation in Large Scale Wireless Sensor Networks", Proceedings of The Sixth IEEE International Conference on Computer and Information Technology (CIT'06).

[13] W. B. Heinzelman, A. P. Chandrakasan and H. Balakrishnan, "An application-specific protocol architecture for wireless micro-sensor networks", IEEE Trans. Wireless Communications, vol. 1, no. 4, Oct. 2002, pp. 660–670.