Sleep Nodes Scheduling in Cluster-Based Heterogeneous Sensor Networks Using AHP

Xiaoling Wu, Jinsung Cho[*], Brian J. d'Auriol, and Sungyoung Lee

Department of Computer Engineering, Kyung Hee University, Korea
{xiaoling,dauriol,sylee}@oslab.khu.ac.kr,
chojs@khu.ac.kr

Abstract. Wireless sensor networks (WSNs) are comprised of energy constrained nodes. This limitation has led to the crucial need for energy-aware protocols to produce an efficient network. The concept of heterogeneity has been introduced in a WSN by deploying a large number of low power sensor nodes and a small number of more powerful nodes to serve as cluster heads (CHs). We propose a sleep scheduling scheme for balancing energy consumption rates in low power sensor nodes based on Analytical Hierarchy Process (AHP). We consider three factors contributing to the optimal nodes scheduling decision and they are the distance to CH, residual energy, and sensing coverage overlapping, respectively. We evaluate the efficiency of our proposed scheme in terms of important network parameters and compare with traditional random sleep scheduling in heterogeneous sensor networks. The proposed scheme is observed to improve network lifetime and conserve energy without compromising desired coverage.

Keywords: Sensor networks, AHP, sleep scheduling, lifetime, coverage.

1 Introduction

Wireless sensor networks (WSNs) are expected to be widely employed in various applications such as medical care, military and environmental monitoring. A typical WSN could contain thousands of small sensors. If these sensors are managed by the base station directly, communication overhead and management complexity could make such a network less energy-efficient. Clustering has been proposed by researchers to group a number of sensors, usually within a geographic neighborhood, to form a cluster. In such a cluster based topology, sensors can be managed locally by a cluster head (CH). Thus the concept of heterogeneity has been introduced in a WSN by deploying a large number of low power sensor nodes and a small number of more powerful nodes to serve as CHs.

The sleeping technique has been used to conserve energy of battery powered sensors. Rotating active and inactive sensors in the cluster, some of which provide redundant data, is an intelligent way to manage sensors to extend its network lifetime.

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[*] Corresponding author.

Y.-H. Lee et al. (Eds.): ICESS 2007, LNCS 4523, pp. 437–444, 2007.

When a sensor node is put into the sleep state, it is completely shut down, leaving only one extremely low power timer on to wake itself up at a later time. This leads to the following sleep scheduling problem: How does the CH select which sensor nodes to be put into sleep, without compromising the sensing coverage of the cluster?

Sleep scheduling which aims to conserve the energy of the sensor nodes has been studied in the literature. In [1], nodes are allowed to sleep based on routing information, and nodes switch between sleep and active state based on the traffic of the network. In [2], a few nodes are selected as coordinators which would then decide the sleep/awake schedule of the other nodes in the network. In [3] nodes are randomly selected to go to the sleep mode and in [4] a linear distance based scheduling has been used to define the sleep schedule of the nodes in a cluster based homogenous network. In [5], the authors release the single hop communication assumption of [4] and introduce a hop-based sleeping scheduling algorithm in a circular sensor network divided by a number of levels. The overall result of these sleep schedules is a considerable reduction in the energy consumption of WSNs.

In this paper, we also investigate this problem and propose a sleeping scheduling scheme based on Analytical Hierarchy Process (AHP). Three factors contributing to the optimal nodes scheduling decision are considered and they are 1) distance to CH, 2) residual energy, and 3) sensing coverage overlapping, respectively. We evaluate the efficiency of our proposed scheme in terms of energy consumption, lifetime and coverage in heterogeneous sensor networks (HSNs).

The rest of the paper is organized as follows. We define the basic assumptions and state the problems in Section 2. The third section presents our sleep nodes scheduling scheme. Section 4 evaluates and analyzes the performance of the proposed method. Finally, we draw the conclusion in Section 5.

2 Problem Statements

We aim to enhance the efficiency of the given sensor network by enabling a balanced usage of energy across the nodes and an improved network lifetime without deteriorating network coverage. Fig. 1 is the illustration of cluster based HSN topology in which our proposed node scheduling scheme will be designed. We focus on energy consumption at the cluster level.

A. Assumptions

We consider the sleep node scheduling problem under several assumptions:

- The target sensor network is heterogeneous with a large number of low power nodes to serve as member nodes and a small number of more powerful nodes to serve as CHs;
- A large number of sensor nodes are deployed over a sensing field, such that at least some sensor nodes can be put into the sleep state without degrading the sensing coverage of the network;
- The CHs can communicate directly with sink and vice- versa. Furthermore, the CH can reach all the sensor members in the cluster in one hop and vice-versa;

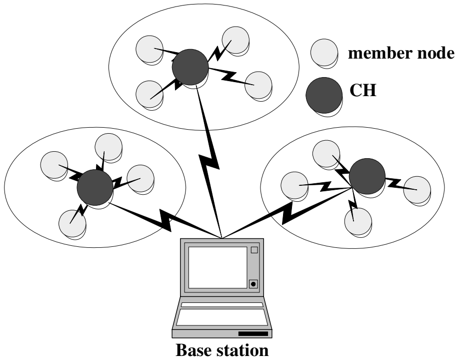

Fig. 1. Cluster based heterogeneous sensor network topology

B. Network Parameters and Energy Model

The user-defined parameters used in defining the network are listed below:

1) Fraction of sleeping nodes in a given round, '*r*': This is the fraction of the total number of nodes in the network that are selected to sleep in each *round*.
2) Threshold limit, 'θ': This denotes the fraction of nodes in the network, which, when dead, determines the lifetime of the network.

We adopt the same radio model as stated in [6] with $\varepsilon_{fs}=10 pJ/bit/m^2$ as amplifier constant, $E_{elec}=50 nJ/bit$ as the energy being dissipated to run the transmitter or receiver circuitry. It is assumed that the transmission between the nodes and their CHs follows a second-order power loss model. The energy cost of transmission for common sensor nodes at distance *d* from its CH in transmitting an *l*-bit data to the CH is calculated as:

$$E_T(l,d) = lE_{elec} + l\varepsilon_{fs}d^2 \tag{1}$$

C. Objectives

To enable load balancing while ensure desired coverage, we put some appropriate nodes to sleep in every cluster. In real WSNs, three factors influence the load balance and coverage directly, that is:

1) Distance to CH: Distance of a node to its CH. It can be approximated by the signal strength of radio transmission. The node with longest distance to the CH is preferred to be put into sleep.
2) Residual energy: Remaining battery of the sensor node. The initial energy is predefined. In addition, the energy consumption for transmission is calculated using Eq. (1) by CH.
3) Sensing coverage overlapping: Overlapped sensing range of a node by neighbor nodes. The node with the largest overlapping degree, i.e., the node with higher redundancy, is desired to be selected as sleeping node.

The optimized sleep nodes scheduling process is a multiple factors optimization problem and can be achieved using AHP which is introduced in the next section.

3 Sleep Nodes Scheduling Scheme by AHP

The Analytical Hierarchy Process (AHP) is a multiple criteria decision-making method which decomposes a complex problem into a hierarchy of simple sub problems (or factors), synthesizes their importance to the problem, and finds the best solution. In this paper, AHP is used to determine the nodes which are eligible to sleep in one cluster. It is carried out in three steps:

1) Collect information and formulate the sleeping nodes selection problem as a decision hierarchy of independent factors.
2) Calculate the relative local weights of decision factors or alternatives of each level.
3) Synthesize the above results to achieve the overall weight of each alternative nodes and choose the one with largest weight as the eligible sleeping node.

A. Structuring Hierarchy

The goal of the decision "select a node eligible to sleep" is at the top level of the hierarchy as shown in Fig. 2. The next level consists of the decision factors which are called criteria for this goal. At the bottom level there exist the *m* alternative sensor nodes to be evaluated.

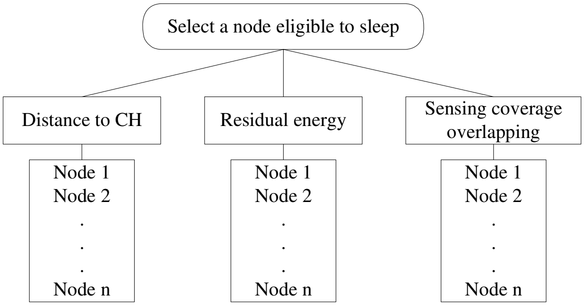

Fig. 2. AHP hierarchy for sleeping nodes selection

B. Calculating Local Weights

Local weights consist of two parts: the weight of each decision factor to the goal and the weight of each nominee to each factor. Both of them are calculated with the same procedure. Taking the former as an example, we describe the procedure as the following three steps.

1) Making Pairwise Comparison

The evaluation matrices are built up through pairwise comparing each decision factor under the topmost goal. The comparison results are implemented by asking the questions: "Which is more important? How much?" and they may be presented in square matrix A as

$$A = \left(a_{ij}\right)_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}, \tag{2}$$

where a_{ij} denotes the ratio of the i^{th} factor weight to the j^{th} factor weight, and n is the number of factors. The fundamental 1 to 9 scale can be used to rank the judgments as shown in Table 1.

Table 1. A fundamental scale of 1 to 9

Number Rating	Verbal Judgment of Preferences
1	Equally
3	Moderately
5	Strongly
7	Very
9	Extremely

2, 4, 6, 8 indicate the medium value of above pairwise comparison.

2) Calculating Weight Vector

For the given matrix A in Eq. (2), we calculate its eigenvalue equation written as $AW = \lambda_{\max}W$, where W is non-zero vector called eigenvector, and $\lambda_{\max}$ is a scalar called eigenvalue. After standardizing the eigenvector W, we regard the vector element of W as the local weight of each decision factor approximately, denoted as:

$$\mathbf{w}_j^T = \{w_1, w_2, \cdots, w_n\} \tag{3}$$

3) Checking for Consistency

If every element in Eq. (2) satisfies the equations $a_{ij}=1/a_{ji}$ and $a_{ik}\cdot a_{kj}=a_{ij}$, the matrix A is the consistency matrix. The evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency ratio (CR), which is defined as the ratio of consistency index (CI) to random index (RI). CI can be achieved by

$$CI = (\lambda_{\max} - n)/(n-1), \tag{4}$$

where

$$\lambda_{\max} = (1/n)\sum_{i=1}^{n}(AW)_i / W_i \,\cdot \tag{5}$$

The *RI* is given in Table 2 [7]. When $CR \le 0.1$, the judgment errors are tolerable and the weight coefficients of the global weight matrix W_j are the weights of decision factor under the topmost goal. Otherwise, the pairwise comparisons should be adjusted until matrix A satisfies the consistency check.

Table 2. Random index

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

C. Calculating Global Weights

From above steps, we can obtain not merely the weights of decision factors towards the topmost goal from W_j but also the weights of alternative nodes towards each factor. If there are eight candidate nodes in each cluster, all the eight weight matrixes of alternatives under three factors construct a 8×3 matrix, denoted as $W_{n_i/j}$, i=1, 2, … 8, j=1, 2, 3. The global weight of each senor node can be achieved through multiplying the local weight by its corresponding parent. So the final weight matrix in the symbol of W_{n_i} is calculated as

$$W_{n_i} = W_{n_i/j} \cdot W_j , \tag{6}$$

where the final weight of each alternative is calculated as

$$W_{n_i} = \sum_{j=1}^{3} W_{n_i/j} \cdot W_j \cdot \tag{7}$$

The larger the final weight of node, the higher the probability of node which is eligible to be put into sleep. Thus, the r fraction of nodes with the largest weight are selected as the sleeping nodes in the current *round.*

4 Performance Evaluations

In order to evaluate the sleep scheduling scheme by AHP, we compare it with random scheduling scheme. We don't compare with other existing work because of our different assumptions. In our simulation, the $50m \times 50m$ square monitored area is assumed. The sensing and communication range is equal to $8m$ and $16m$ respectively. Initial energy in each node is $2J$. We set the total number of nodes N=50 and number of static clusters to be 2. Thus the number of nodes in each cluster is 25 by assuming a uniform distribution of nodes.

In AHP modeling, the matrix A is determined as follows according to Section 3:

$$A = \begin{array}{c c} & \begin{array}{ccc} \alpha & \beta & \gamma \end{array} \\ \begin{array}{c} \alpha \\ \beta \\ \gamma \end{array} & \begin{bmatrix} 1 & 2/1 & 3/1 \\ 1/2 & 1 & 2/1 \\ 1/3 & 1/2 & 1 \end{bmatrix} \end{array}$$

where the three criteria (distance to CH, residual energy and sensing range overlapping) are denoted by α, β and γ respectively.

The computed eigenvector W = [0.5396 0.2970 0.1634]. It indicates the local weight of the distance to CH, residual energy, and sensing coverage overlapping respectively so that we can see that the distance to CH is the most important criterion.

Based on Eq. (5), we get the eigenvalue $\lambda_{\max} = 3.0093$. Consistency ratio can then be calculated as $CR = 0.0047 < 0.1$, thus matrix A satisfies the consistency check.

Each sensor node determines the weight matrixes of alternatives under three factors and then gets global weight based on its specific situation. Its eligibility as a sleeping node can be finally decided by the AHP hierarchy model.

Assume the CH plans to allow 25*r* nodes in its cluster to sleep in each cycle. In the random scheduling scheme, the CH randomly selects *r* fraction sensor nodes to sleep. Fig. 3 provides the energy consumption verses the fraction of sleeping nodes of the two sleep scheduling schemes. It shows that the energy consumption in case of the proposed scheme is less than that of the random scheme. The energy savings can be enhanced with an increasing value of *r*. For an *r* value of “0.7”, the energy consumed is 49.3% less by the proposed scheme than by random scheme.

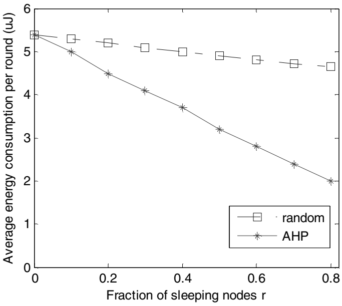

Fig. 3. Energy Consumption in the cluster per round

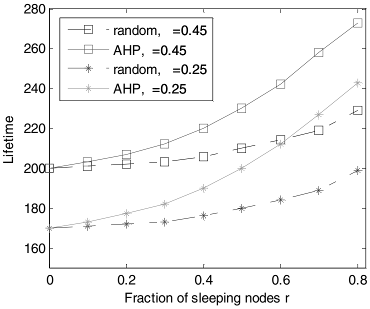

Fig. 4. Lifetime comparison

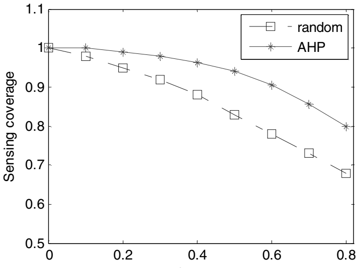

Fig. 5. Coverage verses the fraction of sleeping nodes

Network lifetime can be defined as the time when a fraction of nodes, θ, run out of energy. In Fig. 4, we evaluate the lifetime for various values of *r* and θ. The length of each round is 5*s*. We can see that the lifetime of both schemes is prolonged with the increase of *r* and the proposed scheme greatly outperforms the random scheme. This is in line with the analysis that the proposed scheme can balance the energy consumption among all the member nodes. It also shows that the lifetime of both schemes increases with an increase of θ. This is because the network can be alive up to the time when θ fraction of nodes are drained of their energy.

Fig. 5 provides the comparison of coverage ratio verses the fraction of sleeping nodes *r*. The coverage here is defined as the ratio of the union of all sensor nodes' sensing areas to the whole monitored environment. For the detailed explanation of coverage ratio calculation, please refer to [8]. Fig. 5 shows that for both schemes the coverage ratio decreases with the increase of *r*. However, in case of the proposed AHP based sleeping scheme, the coverage ratio still can maintain above the desired value of 0.98 when up to 30% nodes are put into sleep. It indicates that the tradeoff in terms of coverage is not very critical by using the AHP based scheme.

5 Conclusion

In this paper, we proposed a sleep scheduling scheme for balancing energy consumption rates in HSNs based on AHP. Three factors contributing to the optimal nodes scheduling decision are considered and they are the distance to CH, residual energy, and sensing coverage overlapping, respectively. We evaluated the efficiency of our proposed scheme in terms of energy consumption, lifetime and coverage ratio, and compared with traditional random sleep scheduling scheme in heterogeneous WSNs. The proposed scheme was observed to improve network lifetime and conserve energy without compromising the sensing coverage of the cluster.

Acknowledgments. This research was supported by the MIC (Ministry of Information and Communication), Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute of Information Technology Advancement) (IITA-2006-C1090-0602-0002).

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