An Active Node Set Maintenance Scheme for Distributed Sensor Networks

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Abstract. In this paper, we propose an energy-efficient coverage maintenance scheme for prolonging the lifetime of the sensor networks. Researchers are actively exploring advanced power conservation approaches for wireless sensor network and probabilistic approaches among them are preferred due to advantages of simplicity. However, these probabilistic approaches have limited usefulness because they can not ensure full area coverage. In the proposed scheme, each node computes the probability through the densities of its own coverage and keeps it adaptively to the report history. The performance of proposed scheme is investigated via computer simulations. Simulation results show that the proposed scheme is very simple nevertheless efficient to save the energy.

1 Introduction

Recently, the idea of wireless sensor networks has attracted a great deal of research attention due to wide-ranged potential applications that will be enabled by wireless sensor networks, such as battlefield surveillance, machine failure diagnosis, biological detection, home security, smart spaces, inventory tracking, and so on [7][9][10][13].

A wireless sensor network consists of tiny sensing devices, deployed in a region of interest. Each device has processing and wireless communication capabilities, which enable it to gather information from the environment and to generate and deliver report messages to the remote sink node. The sink node aggregates and analyzes the report message received and decides whether there is an unusual or concerned event occurrence in the deployed area. Considering the limited capabilities and vulnerable nature of an individual sensor, a wireless sensor network has a large number of sensors deployed in high density and thus redundancy can be exploited to increase data accuracy and system reliability. In a wireless sensor networks, energy source provided for sensors is usually battery power, which has not yet reached the stage for sensors to operate for a long time without recharging. Moreover, sensors are often intended to be deployed in remote or hostile environment, such as a battlefield or desert; it is undesirable or impossible to recharge or replace the battery power of all the sensors. However, long system lifetime is expected by many monitoring applications. The system lifetime, which is measured by the time until all nodes have

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been drained out of their battery power or the network no longer provides an acceptable event detection ratio, directly affects network usefulness. Therefore, energy efficient design for extending system lifetime without sacrificing system reliability is one important challenge to the design of a large wireless sensor network. In wireless sensor networks, all nodes share common sensing tasks. This implies that not all sensors are required to perform the sensing task during the whole system lifetime. Turning off some nodes does not affect the overall system function as long as there are enough working nodes to assure it. Therefore, if we can schedule sensors to work alternatively, the system lifetime can be prolonged correspondingly; i.e. the system lifetime can be prolonged by exploiting redundancy.

A number of studies for reducing the power consumption of sensor network have been performed in recent years. These studies mainly focused on a data-aggregated routing algorithm [1 – 4] and energy efficient MAC protocols [6 – 8]. However, for more inherent solution to reduce energy consumption problem, the application level should be also considered [9][12]. In addition, the sensing area of each node may overlap because each link of a path to the sink node should be less than the radio radius. Therefore, it is important to reduce unnecessary traffic from overlapping sensing areas. Researchers are actively exploring probabilistic approaches due to its simplicity of distributed manner. However, these probabilistic approaches have limited usefulness because they can not ensure full area coverage. To guarantee the full coverage, our scheme maintains the report probability adaptively to the report history. Namely, each node calculates its report probability based only on the number of neighbors. Each node decides to report the message through the probability, and re-computes the probability using the report history. In other words, the probability of the node, which has transmitted at the previous report period, is decreased to avoid successive reporting. Reversely, uncovered area has more probability of sensing, that is covering, in the next period. The performance of proposed scheme is investigated via computer simulations. Simulation results show that our approaches reduce the report of redundant packets. Our paper is organized as follows. Section 2 reviews related works and section 3 introduces our scheme. In section 4 simulation results are presented, and finally, section 4 presents our conclusions.

2 Related Works

Sensor nodes are usually scattered in a sensor field. Each of these scattered sensor nodes is capable of collecting data and routing it back to the sink. Data are routed back to the sink by a multihop infrastructureless, and self-organized architecture. The sink may communicate with the task manager node via Internet or satellite.

In recent years, several important theoretical evaluations of coverage maintenance have been studied. These studies mainly analyze the distributed constructing and routing algorithms of a connected dominating set (CDS) [1 – 4]. In [4], Gao et al. present a randomized algorithm for maintaining a CDS with low overhead. The algorithm assumes the grid partition of the coverage and selects a small number of cluster heads. The work show that the total number selected has an approximation factor of $O(\sqrt{n})$ of the minimum theoretically possible. Wang et al. suggest a geometric spanner algorithm that can be implemented in a distributed manner in [2]. The degree of node is limited by a positive constant, and the resulting backbone is a spanner for both hops and length. In [3], Alzoubi et al. describe a distributed algorithm for constructing a minimum connected dominating set (MCDS) with a constant approximation ratio of the minimum possible and linear time complexity. The above algorithms provide the theoretical limits and bounds of what is achievable with coverage maintenance. However, there is poor correlation between the spatial distance and reception rate, so assumptions based on geographic proximity between nodes do not necessarily hold in practice. Furthermore, the radio propagation is not circular, presenting non-isotropic properties. Therefore, the approximations under these assumptions may cause serious problems with algorithms that assume bidirectional connectivity [13].

The energy efficient protocols of MAC layer approach turn off the radios and do not transmit or receive of packets in a particular (usually small) timeframe. These protocols usually trade network delay for energy conservation because of the startup cost associated with turning the radios back on. Sohrabi and Pottie [6] propose a self-configuration and synchronization TDMA scheme at the single cluster. This work is more focused on the low-level synchronization necessary for network self-assembly, while we concentrate on efficient multihop topology formation. Sensor-MAC (S-MAC) [7] periodically turns off the radios of idle nodes and uses in-channel signaling to turn off radios that are not taking part in the current communication. More recent work [8] continues to explore MAC-level wake-up schemes. Most of the MAC schemes mentioned above can be applied to our scheme. Our scheme focuses on the method of generating report message, and thus independent to the MAC level approaches.

Another approach in reducing energy consumption has been to adaptively control the transmit power of the radio. The lazy scheduling proposed in Prabhakar et al. [9] transmits packets with the lowest possible transmit power for the longest possible time such that delay constraints are still met. Ramanathan and Rosales-Hain [10] proposed some distributed heuristics to adaptively adjust node transmit powers in response to topological changes caused by mobile nodes. This work assumes that a routing protocol is running at all times and provides basic neighbor information that is used to dynamically adjust transmit power. While power control can be very useful, particularly in asymmetric networks such as cellular telephony, their advantages are less pronounced in sensor networks [5]. In Xu et al. [11], GAF nodes use geographic location information to divide the network into fixed square grids. Nodes in each grid alternate between sleeping and listening, and there is always one node active to route packets per grid. Our scheme does not need any location aids since it is based on connectivity. Chen et al. [12] proposed SPAN, an energy efficient algorithm for topology maintenance, where nodes decide whether to sleep or join the backbone based on connectivity information supplied by a routing protocol. Our scheme does not depend on routing information nor need to modify the routing state; it decides whether to generate a report message or not based on adaptive report probability. In addition, our work does not presume a particular model of fairness or network capacity that the application requires.

3 Proposed Scheme

Due to the tight restrictions of the sensor node, low power consumption is one of the most important requirements. In addition, fairness is also a major requirement for construction of efficient sensor networks. To satisfy the requirements for self-organizing wireless sensor networks, we suggest a distributed scheme of controlling the transmission of sensing data by considering the geographical density of nodes. Namely, each node makes a report rule based on the geographical density and determines whether transmit the sensing data or not through the rule. In the proposed scheme, the rule is defined as a probabilistic approach. Therefore, each node determines whether transit the sensing data or not using the report probability.

All nodes investigate the densities, share the densities with their neighbors, and compute the report probabilities. For the simplicity, we define the density of node *i*, denoted by $n_i.d$, as follows:

$$n_i.d = \frac{1}{\|n_i.nn\|} \qquad \text{for } i = 1, 2, 3, \ldots \tag{1}$$

where $n_i.nn$ is the set of neighbor IDs of i^{th} node.

In addition, the average density of neighbors can be expressed by

$$n_i.n\bar{d} = \frac{\sum_{k \in n_i.nn} n_k.d}{\|n_i.nn\|} \qquad \text{for } i = 1, 2, 3, \ldots \tag{2}$$

Using (1) and (2), the report probability of node *i* at first report period, denoted by $n_i.p_0$, can be defined as

$$n_i.p_0 = \begin{bmatrix} 0 & : \|n_i.nn\| = 0 \\ \min(1,\ \alpha n_i.d + (1-\alpha) n_i.a\bar{d}) & : \|n_i.nn\| \neq 0 \end{bmatrix} \qquad \text{for } i = 1, 2, 3, \ldots \tag{3}$$

where α is scaling factor and $\|n_i.nn\| = 0$ means that n_i has no neighbors. Note that the node without neighbors needs not to gather or transmit sensing data.

As mentioned above, probabilistic approaches may consume a long time for covering entire area due to their randomness. In our scheme, the report probability is maintained adaptively to the report history for solving these problems. The report history means whether a report is performed or not at previous report period, and can be expressed by

$$h(j) = \begin{bmatrix} -1: \text{has transmitted at } (j\text{-}1)^{\text{th}} \text{ period} \\ 1: \text{has not transmitted at } (j\text{-}1)^{\text{th}} \text{ period} \end{bmatrix} \tag{4}$$

Using (3) and (4), the report probability of node *i* at j^{th} report period, denoted by $n_i.p_j$, can be calculated as

$$n_i.p_j = n_i.p_{j-1} + h(j)\beta, \qquad \text{for } i, j = 1, 2, 3, \ldots \tag{5}$$

where β is the adaptivity factor.

To validate the performance of the proposed scheme, several terms are needed to be defined. The reachability is very important factor to determine the number of nodes should be scattered over the sensor field. The reachability, denoted by *RE*, can be defined as the number of nodes that can deliver the sensing information to the sink and can be obtained by

$$RE = \frac{\eta}{N} \cdot 100 \tag{6}$$

where η denotes the number of nodes that have a path to the sink and *N* means the number of deployed nodes.

Sensing degree is another factor for sensor networks. We divide sensing field into 1 x 1 unit grids to compute sensing degree and coverage. Therefore, sensing degree can be computed by the average sensing redundancy of a grid. To explain the redundancy of a grid (*x*, *y*), we define the redundancy function $f(i, x, y)$ as follows:

$$f(i,x,y) = \begin{cases} 1 : \sqrt{(n_i.x - (x+0.5))^2 + (n_i.y - (y+0.5))^2} \le r \\ 0 : \sqrt{(n_i.x - (x+0.5))^2 + (n_i.y - (y+0.5))^2} > r \end{cases} \tag{7}$$

where *r* denotes the radio radius, and $n_i.x$ and $n_i.y$ are the *x* and *y* coordinates of i^{th} node, respectively. In addition, *X* and *Y* are the width and vertical length of sensor field, respectively.

Then, we can compute the density of a grid $d_{x,y}$ as follows:

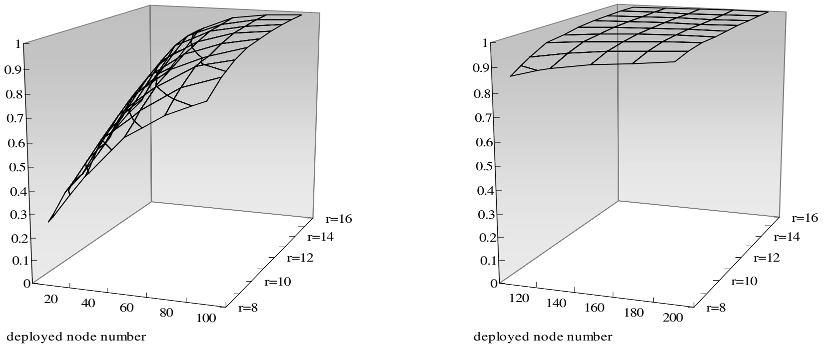
$$d_{x,y} = \sum_{i=1}^{N} \sum_{x=1, y=1}^{X,Y} f(i,x,y) \tag{8}$$

Next, sensing degree, denoted by *SD*, can be calculated by

$$SD = \frac{d_{x,y}}{XY} \tag{9}$$

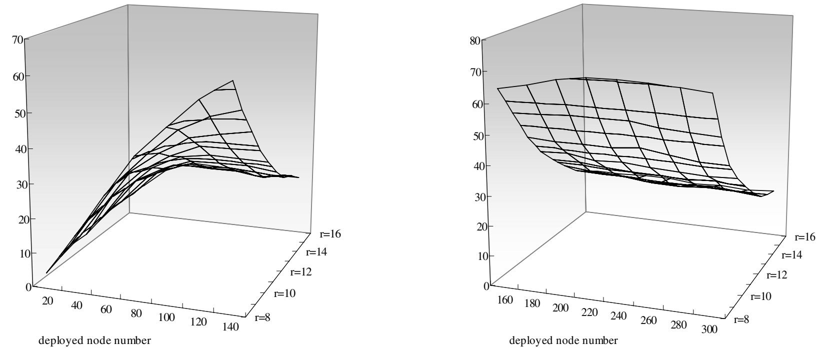
4 Simulations

To analyze the performance of our scheme, we carry out some experiments in static networks. We deploy 100 nodes in a square space (100 x 100). Nodes' x- and y-coordinates are set randomly. Each node has a sensing range of 15 meters and knows its neighbors. Note that the position, the neighbors are located, is not necessary in our scheme. We let each node decide whether to report or not based on its report probability. The decision of each node is visible to the neighbors. The nodes, which make decisions later, cannot "see" the nodes that have been turned off before. The current sensing coverage by active nodes is compared with the original one where all nodes are active. To calculate sensing coverage, we divide the space into 1m×1m unit grids. We assume an event occurs in each grid, with the event source located at the center of the grid. We investigate how many original nodes and how many active nodes can detect every event. In this experiment, we assume that the sensing coverage of node is similar to the radio coverage because the node can deliver the sensing information via only radio. In fact, the existence of an optimal transmission radius in the request-spreading process suggests an advantage in having a transmission radius larger than the sensing radius because the sensing radius directly affects the average distance between area-dominant nodes. Moreover, enlarging the transmission radius can also benefit data-fusion schemes by allowing the construction of better-balanced trees. We plan to study sensor networks in which the sensing and transmission radius are different in the future. In our simulation, we assumed that the sink node is located in the center of the sensor field. Fig. 1 shows a 3D surface plot of the reachability in different sensing range and deployed node numbers. We change node density by varying the sensing range, denoted by *r*, from 6 to 16 and the deployed node number from 20 to 100 (Fig. 1a) and from 120 to 200 (Fig. 1b) in the same 100m×100m deployed area. From it, we can see that increasing the number of the deployed nodes and increasing the sensing range will result in more nodes being idle, which is consistent with our expectation. As shown in this Fig. 1b, the reachability reaches 1 when the number of deployed nodes is over 100. It indicates that most of deployed node can find route to the sink node when the number of deployed nodes is over 100.



(a) Deployed node number: 20 ~ 100 (b) Deployed node number: 120 ~ 200

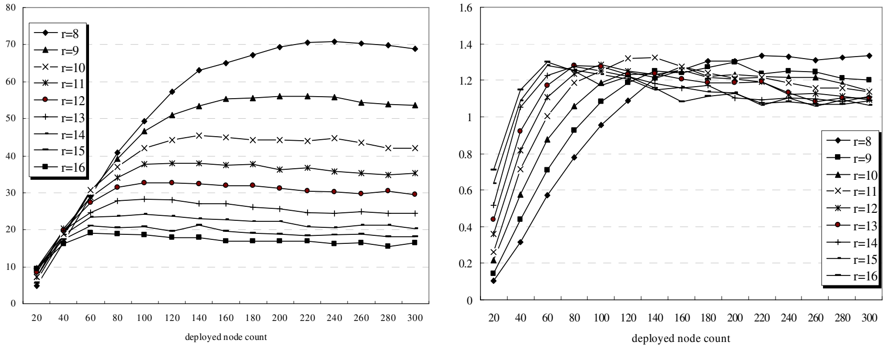
Fig. 1. Reachability vs. node density



(a) Deployed node number: 20 ~ 140 (b) Deployed node number: 140 ~ 300

Fig. 2. Number of active nodes vs. node density

Fig. 2 shows 3D surface plot of the number of active nodes in different sensing range and deployed node numbers. We change node density by varying the sensing range, denoted by *r*, from 6 to 16 and the deployed node number from 20 to 100 (Fig. 2a) and from 120 to 200 (Fig. 2b) in the same 100×100 deployed area. We can also see that the active node number remain constant over different deployed node number when the sensing range and deployed area are fixed. These trends can be observed more precisely as illustrated in Fig. 3a. It means that the calculation of idle node is very easy using our scheme and can be easily applied to various MAC level power saving approaches.



(a) Active node number

(b) Sensing degree

Fig. 3. Active node number and sensing degree vs. node density

We also investigate the sensing degree vs. node density. As shown in Fig. 3b, since nodes deployed on the sensing area densely enough, the sensing degree approximates 1 ~ 1.4. This indicates that our scheme reaches optimal solution. In Fig. 4, sensing degree of out scheme is compared with original sensing degree.

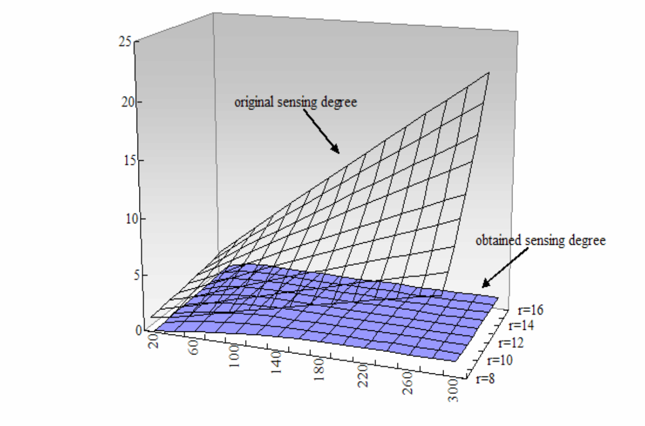
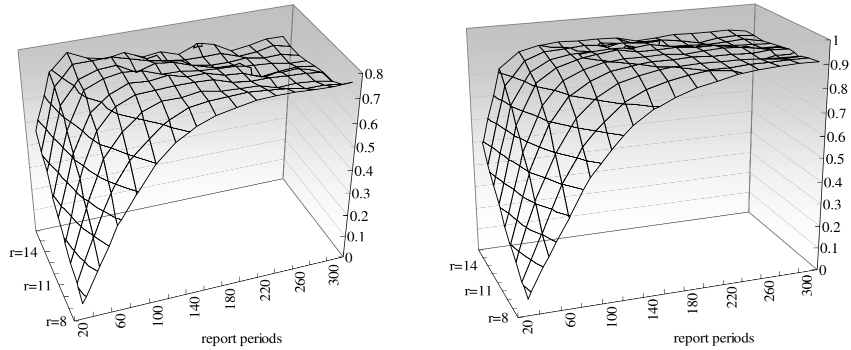


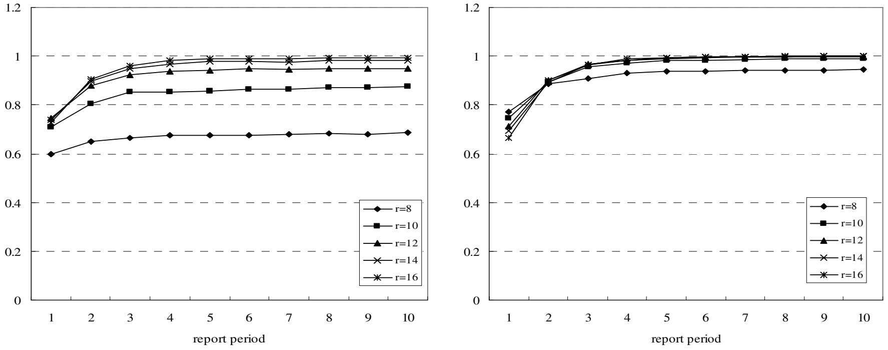
Fig. 4. Sensing degree reduction vs. node density

Fig. 5 presents the same effectiveness but from the different view: the ratio of the covered area. We still divide the space into 1 ×1 unit grids as mentioned earlier. An event occurs in each grid, with the event source located at the center of the grid. We

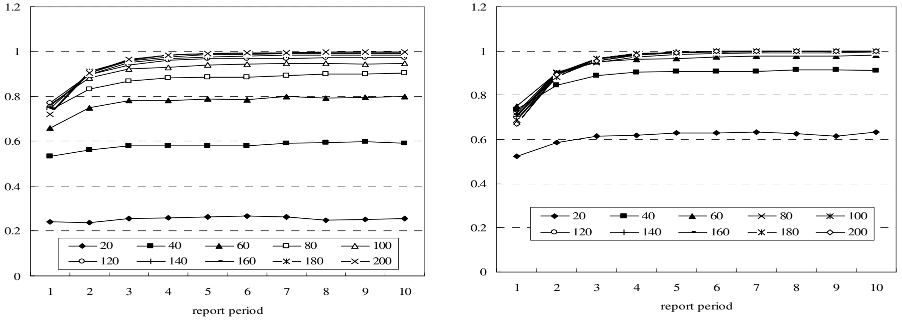


(a) Sensing coverage at 1st report (b) Sensing coverage at 2nd report

Fig. 5. Sensing coverage vs. node density



(a) Sensing coverage vs. range (N=100) (b) Sensing coverage vs. range(N=200)



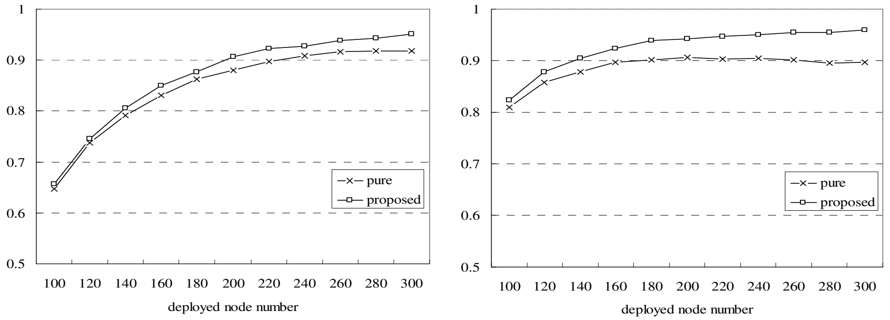
(c) Sensing coverage vs. node density (r= 12) (d) Sensing coverage vs. node density (r = 18)

Fig. 6. Sensing coverage vs. report period

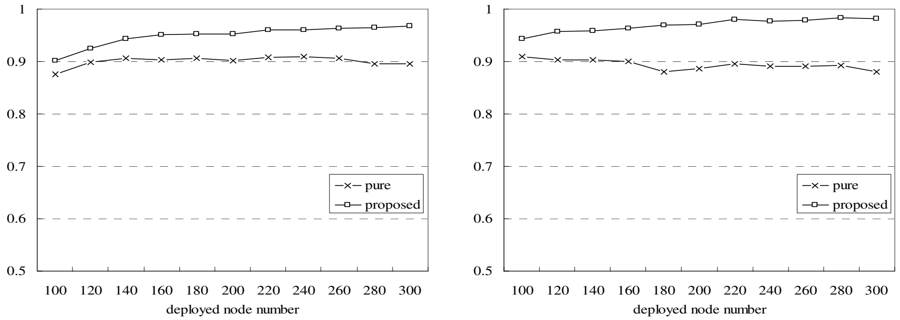
investigate the ratio of the grid number reached by active nodes to the total number of grids when sensing range is in from 8 to 16. As illustrated in the figures, most of the area, above 80%, can be covered by our scheme.

In the above figures, a pure probabilistic approaches and the proposed scheme don't have differences because the proposed scheme performed actively to the report history. Therefore, Fig. 6 and Fig. 7 show the sensing coverage vs. report history. First, Fig. 6 depicts the ratio of the covered area with changing the report period. We investigate the ratio of the grid number reached by active nodes to the total number of grids using pure probabilistic approaches when report period is in from 1 to 10. As illustrated in the figures, most of the area, after 4th period, can be covered by pure probabilistic approaches.

Next, we are going to compare the proposed scheme with pure probabilistic approach at the 2nd report period. Fig. 6 shows the ratio of the covered area of pure probabilistic approach and proposed scheme with changing the report period. As showed in these figures, proposed scheme reaches at 1 more quickly than pure probabilistic approach.



(a) Sensing coverage vs. node density (r= 8) (b) Sensing coverage vs. node density (r = 10)



(c) Sensing coverage vs. node density (r= 12) (d) Sensing coverage vs. node density (r = 14)

Fig. 7. Sensing coverage at 2nd report period

5 Conclusions

This paper presents a scheme for reducing the redundant power consumption in self-organizing wireless sensor networks. Our scheme computes adaptive report probability and controls a packet report through the probability. The performance of our scheme is investigated deeply via computer simulations, and the results show that our scheme is very simple nevertheless efficient to save energy.

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