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Controlled deployments for wireless sensor networks

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Abstract: In wireless sensor networks (WSNs), the operation of sensor nodes has to rely on a limited supply of energy (such as batteries). To support long lifetime operation of WSNs, an energy-efficient way of sensor deployment and operation of the WSNs is necessary. A new controlled layer deployment (CLD) protocol to guarantee coverage and energy efficiency for a sensor network is proposed. CLD outperforms previous similar protocols in that it can achieve the same performances and guarantee full area coverage and connection using a smaller number of sensors. It can also ameliorate the 'cascading problem' that reduces the whole network lifetime. Finally, analysis and simulation results show that CLD can use fewer sensor nodes for coverage and also increases the lifetime of the sensor network when compared with the probing environment and adapting sleeping (PEAS) protocol.

1 Introduction

The wireless networks have made many communication applications more convenient during the past years. They include the mobile phones, bluetooths, short distance communication networks, mobile ad hoc networks and the wireless sensor networks (WSNs). WSNs can be applied in many domains such as military, medicine, biology, industry, life-technology and so on. The applications require long-term monitoring of the environments to assist people in making decisions. In addition, these environments are often inaccessible or unsuitable for people to work into. Thus, a WSN can be used as a substitute when conducting the more difficult monitoring tasks.

The WSN has the following characteristics: small size, multi-purpose (e.g. independent detection, brief recording, simple computation, short distance communication and so on) and uses mutual co-operation to attain the overall goal [1]. One of its biggest limiting factors is its insufficient power, resource. In this paper, we propose a full area coverage and connection distributed protocol with energy efficiency in order to increase the whole network lifetime and sensor coverage. The aim of the full area coverage and connection is to guarantee the integrity of the surveillance area information and to solve the mobility problem of monitored objects. For example, assume an animal being monitored in a full area coverage and connection is moving around within a given surveillance area. No matter where the animal moves, the sensor network can still obtain complete information of the animal.

In general, the WSNs can contain hundreds or even thousands of sensing nodes. It is desirable to make these nodes as energy-efficient as possible and to rely on their large numbers in order to obtain high-quality results. Likewise, the sensor network routing protocols must be designed to achieve fault tolerance in the presence of individual node failures while also minimising energy consumption. Moreover, as the limited wireless channel bandwidth must be

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shared by all the sensors in the network, routing protocols for these networks should be able to perform local collaborations in order to reduce the bandwidth requirements. Eventually, the data being sensed by the nodes in the network must be transmitted to a control centre (i.e. the sink) or a base station where the end sensor nodes can access the data. At present, there are many routing methods in the WSNs. The direct transmission energy protocol [2] proposed that each sensor node transmits the data directly to the sink, not through intermediate nodes in order to shorten the transmission time. Its disadvantage is that the sensor nodes will have larger power consumption, thereby shortening the lifetime of the sensor nodes and leaving behind only a few active sensor nodes besides the sink. The minimum transmission energy (MTE) protocol [2] is an indirect hop-by-hop communication scheme and is a better power-saving communication protocol between end sensor nodes. It uses intermediate nodes to transmit data to the sink. The advantage of this schemeis its power-saving feature, but it creates more work overheads on the intermediate nodes and thus reduces its lifetime. In particular, those sensor nodes nearest to the sink have shorter lifetimes because the sensor nodes require more frequent reception and transmission of data. The low-energy adaptive clustering hierarchy (LEACH) protocol [2] is an improved indirect communication scheme. Its main characteristic is the use of the hierarchy transmission communication. Sensor nodes transmit data through an area cluster head [3–5] to the sink. As an area cluster head is randomly played by each sensor node, the energy consumption of each sensor node is more even. However, the cluster head must communicate with the sink on one hand, and it must also communicate with the sensor nodes on the other hand. Thus, the work overhead of the cluster head is quite heavy.

The two-tier data dissemination (TTDD) protocol [6] is also an improved indirect communication scheme. Its speciality is the use of a virtual grid, dual-layer transmission communication similar to the grid communication [7–9]. This method uses massive sensor nodes deployed in the sensing area and equally divides the sensing area by virtual grids. The sensor node nearest to the virtual grid is like the sink which has a continuing communication transmission role. Hence, the sensor node can transmit data to the nearest sink through the sensor node nearest to the virtual grid which transmits it to the source. This scheme is suitable for a large-scale WSN, but its drawback is that it requires a massive amount of sensor nodes. In the fixed transmission ranges protocol [10, 11], all sensor nodes have a fixed transmitting range when considering a full area coverage and connection. The disadvantage of this broadcasting protocol is that it creates blind flooding and many excess transmissions which lead to several collisions in the media access control layer. Eventually, it is bad to network efficiency and subsequently reduces the whole network lifetime. The adjustable transmission ranges protocol [10, 12] uses sensor nodes to monitor their distance from one another, as well as transmits and receives using the smallest power signal and the smallest power consumption, respectively. Thus, the whole network lifetime is prolonged. Its disadvantage is that the adjustment of the transmission power intensity creates a network topology change that leads to network-connectivity failure. Therefore it is imperative to manage the transmission area of the sensor nodes in order to maintain network connectivity. In the coverage-preserving node scheduling scheme [10, 13], each sensor node knows the position of all its neighbouring nodes when considering full area coverage and connection. When a sensor node knows the other node, it does not need to send out a message because it already covers its own monitoring area. This sensor node will transmit a 'withdrawal' message to notify all its neighbours. At the same time, it will enter into a sleeping mode in order to attain an energy-saving effect. The disadvantage of this method is that when a sensor dies, the other sensors must have a prior knowledge of all its neighbours in order to substitute for the unattended area.

Apparently, the most commonly encountered problems of the typical WSN between the sink and the sensor node data transmission are as follows: (1) The farthest sensor nodes from the sink will exhaust more network resources (e.g. bandwidth) and consume more power and consequently, the whole network efficiency and lifetime are reduced. (2) When the sensor nodes are making data transmissions, intermediate nodes are usually needed to help in data forwarding, especially in the hop-by-hop protocol system (e.g. MTE routing protocol). The farther it is to the sink, the more intermediate nodes are needed and thus causes more power consumption in the intermediate nodes. The nearer the intermediate nodes are to the sink, the shorter their lifetimes because of the increase in the data transmission frequency. Ultimately, the whole network lifetime is reduced. This is referred to as the cascading effect [2].

Probing environment and adapting sleeping (PEAS) [14] does not consider the cascading effect. Furthermore, PEAS assumes that sensor nodes are deployed randomly. Thus usually we need a lot of sensors to guarantee a complete coverage. In this paper, we also focus on how to solve the problem of full coverage and connection encountered in WSNs. Coverage and deployment-related problems have been studied before [13–25]. However, in situations where we can control the arena of deployment, a systematic deploying method can reduce the number of sensors used and save the energy consumption without diminishing the functionalities of the network. Therefore we propose a controlled layer deployment (CLD) protocol that uses the concept of virtual grids for working node placements to achieve the same effective full area coverage and connection. CLD also considers the above-mentioned cascading problem by deploying more backup nodes near the sink. Finally, we show the results of the analysis and simulation to prove that the new protocol can use fewer sensor nodes for coverage and increase its lifetime longer than that of the PEAS protocol.

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The remainder of this paper is organised as follows. Basically the states and workings of sensors are the same in both CLD and PEAS. In Section 2, we first introduce the operation of sensors in the PEAS protocol. Section 3 discusses in detail the design concept, operation analysis, deployment steps, route establishment and maintenance mechanism of the CLD. Section 4 shows the experimental results, analysis and discussions. Finally, Section 5 gives the conclusion and future works.

2 PEAS protocol

PEAS [14] is an energy-saving protocol aiming at full area coverage and connection. It uses massive small sensors of short energy lifetime and maintains a necessary small working sensor set. It turns off excess sensor nodes in order to save energy to establish a long running and flexible WSN. The characteristic of the PEAS energy-saving protocol is that it can endure the high malfunction rate of sensor nodes. It will also result in the high change of the whole WSN topology. PEAS can initiate the probing of the condition of the neighbouring area working nodes at anytime in order to replace the faulty sensor nodes.

CLD adapts the spirits of PEAS that only a small set of sensor nodes is in the working state. Other nodes are in sleeping states but wake up intermittently to probe its environment for the existence of nearby working nodes. In the following, we briefly describe the design goal and method of the PEAS protocol.

2.1 Sensor states

The goal of the protocol is to maintain a suitable and small number of working nodes in order to save energy. A sleeping sensor node will automatically awaken and, within its own probing range (R_p), transmit a probing message in order to determine if there are still some working nodes existing in the neighbouring area. If yes, it will receive a REPLY message sent by the working node. This REPLY message contains the desired probing rate of the application and the measured probing rate perceived by the working node. After receiving the REPLY message, a sleeping node will calculate the next wake-up time and go back to sleep and to wait for the next wake-up. If there is no reply to the probing message, the sensor node will awaken and serve as the working node. The three major operating states are shown in Fig. 1.

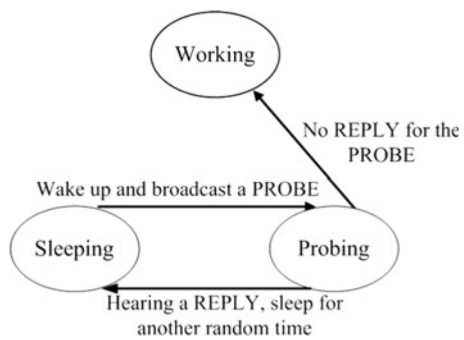

Figure 1 *The sensor state in PEAS*

There are two major design decisions for determining the probing range in order to establish a robust sensing and communication for a stable connected network: (1) the probing range should be able to let a sleeping node decide if it should awaken and become a working node, and guarantee that the adjustment of the working nodes are at suitable distances and (2) the probing rate should also be randomised to prevent and shorten the gaps between the times that there are no working nodes because of the malfunctioning of the sensor nodes.

2.2 Adaptive sleeping

Adaptive sleeping decides when a sleeping sensor node will awaken to probe. It decides the probing rate of each sleeping sensor node and provides the guarantee that the sleeping nodes, dispersed in each area, will awaken periodically to do probing. The probing rate must be controlled properly. It must be optimised in order to minimise the probing overhead. The probing rate is determined by the following probability density function $f(t_s) = \lambda e^{-\lambda t_s}$ where λ is the probing rate of the node and t_s is the sleeping time duration. For details about how to update the probing rate for the sleeping nodes, see [6].

To show that PEAS can achieve a connected sensor network asymptotically, the following lemma is proved. First, we define the following variables: d is the dimension of the sensor space, n the number of sensor nodes, k a constant, R_p the probing range, R_t the maximum transmitting range, c the side length of a square cell (range of each basic cell) [26] and L the sensor distribution range (range of where all sensor nodes are distributed) [26].

Lemma 1: Consider the case when n nodes are uniformly distributed in $R = [0, L]^d$. For $d = 2$, and assume that $c^d n = kL^d \ln L$ for some constant $k > 0$. Let $\mu_0(n)$ be the random variable denoting the number of empty cells. If $k > d$, then $\lim_{L\to\infty} E[\mu_0(n)] = 0$, where $E[\mu_0(n)]$ is the expected number of empty cells.

From the above, we have Lemma 2.

Lemma 2: For any working node A and its working neighbour B, $\lim_{L\to\infty} P[\min(\text{Dist}(A, B) < (1 + \sqrt{5})c] = 1$, where Dist(A,B) denotes the distance between A and another working node B.

Finally, the paper states the following theorem based on the above two lemmas.

Theorem 1: If the transmitting range $R_t \geqq (1 + \sqrt{5})R_p$, and the conditions in Lemma 1 are satisfied, then $\lim_{L\to\infty}$

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