Energy Enhancement in Wireless Sensor Networks through Distributed Fibre Sensor

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Abstract—Based on the protocol—low-energy adaptive clustering hierarchy (LEACH), we investigate an improved energy-efficient communication protocol for wireless sensor networks (WSNs) in the presence of distributed optical fiber sensor (DFS) links located at the centre of WSN fields. Network performances in terms of lifetime of nodes are simulated for the cases that two WSNs can or cannot communicate with each other. The lifetime of such sensor network with rectangular topology is further investigated.

Index Terms—Distributed optical fiber sensor, low-energy adaptive clustering hierarchy (LEACH), protocol, sensor network, wireless sensor network.

I. INTRODUCTION

WIRELESS SENSOR NETWORK (WSN) has attracted considerable attentions during the last few years due to characteristics such as feasibility of rapid deployment, self-organization (different from ad hoc networks though) and fault tolerance, as well as rapid development of wireless communications and integrated electronics [1]. Such networks are constructed by randomly but densely scattered tiny sensor nodes [Fig. 1(a)]. As sensor nodes are prone to failures and the network topology changes very frequently, different protocols have been proposed to save the overall energy dissipation in WSNs [2]–[5]. Among them, Low-Energy-Adaptive-Clustering-Hierarchy (LEACH), first proposed by researchers from Massachusetts Institute of Technology [5], is considered to be one of the most effective protocols in terms of energy efficiency [6], [7].

On the other hand, distributed fiber sensors (DFS) have been intensively studied or even deployed for analyzing loss, external pressure, temperature or birefringence distribution along the fiber link, ranging from hundreds of meters to tens of kilometers [8]–[13]. Mechanisms include Rayleigh, Brillouin, or Raman scattering or polarization effects, through either time or frequency-domain analysis. Compared with conventional sensors including wireless ones, optical fiber sensors have intrinsic advantages such as high sensitivity, the immunity to electromagnetic interference (EMI), superior endurance in harsh environments and much longer lifetime.

Apparently it would be highly desirable to have integrated sensor networks that can take advantages of both WSNs and optical sensor networks (OSNs). Such hybrid sensor network can find major applications including monitoring inaccessible terrains (Military, high-voltage electricity facilities, etc.), long term observation of earthquake activity and large area environmental control with tunnels, and so on. Especially under harsh environments (e.g., high humidity, strong EMI, etc.), OSN has to be deployed. So far, hybrid sensor networks have been studied as well [14]–[16], while optical sensors in these networks are generally point-like (e.g., fiber-Bragg-grating based), and such nodes can be regarded as normal WSN nodes after optical to wireless signal conversion.

In this paper, we investigate an infrastructure of a sensor network that is composed of a DFS link and two separated WSNs, as shown in Fig. 1(b). The DFS link is located at the center of the whole sensor field and can cover a certain area. The two WSN fields are filled with randomly scattered nodes as usual. These nodes can or cannot communicate with each other depending on the application.
requirements. Unlike simple WSNs, since the DFS has to be powered on for data processing (as an activesensor “link” without energy restriction), we use one end of the DFS as the sink or the base station (BS) for all WSN nodes. Although the performance (lifetime) of the DFS may have to be considered as well, here we assume that the lifetime of such a sensor network is mainly determined by the WSN. We specially investigate an improved energy efficient communication protocol, optical LEACH (O-LEACH), based on the WSN LEACH protocol. The performance of the whole sensor network is simulated under different scenarios. We find that such clustering-based protocol still exhibits good energy efficiency in the sensor network, especially when two WSNs are not reachable to each other. In addition, as the DFS may cover a long rectangular area (up to tens of kilometers), O-LEACH protocol is used to investigate the lifetime of the hybrid sensor network with rectangular topology by dividing and linking a series of WSNs around the DFS.

![Diagram of a WSN with randomly scattered nodes and DFS link](image1)

**II. O-LEACH PROTOCOL**

As only nodes of two WSNs are energy or power limited, the protocol is mainly dealing with these nodes, starting from random node positioning outside the DFS coverage area, while inside the phenomenon. As the LEACH protocol is one of the most popular WSN protocols, here we only give a brief introduction about that and more details could be found in [1] and [5]. LEACH is a cluster-based protocol. In the protocol, the sensor nodes in the network are divided into a number of clusters, the nodes organize themselves into preferred local clusters, a sensor node is selected randomly as the cluster head (CH) in each cluster, and this role is rotated to evenly distribute the energy load among nodes of the network. The CH nodes compress data arriving from nodes that belong to the respective cluster, and send an aggregated packet to the BS in order to further reduce the amount of information that must be transmitted to the BS, thus reducing energy dissipation and enhancing system lifetime. After a given interval of time, randomized rotation of the role of CH is conducted to maximize the uniformity of energy dissipation of the network. Sensors elect themselves to be local cluster heads at
any time with a certain probability. Generally, only $\%$ of nodes need to act as CHs based on simulation results. LEACH uses a TDMA/CDMA MAC to reduce inter-cluster and intra-cluster collisions. As data collection is centralized and performed periodically, this protocol is most appropriate when there is a need for constant monitoring by the sensor network.

The flowchart of the O-LEACH protocol is shown in Fig. 2. As the operation of the standard LEACH protocol is separated into the setup phase and the steady phase, we also separate the O-LEACH operation into two phases, and the steady phase is as same as the LEACH one [5]. During the setup phase, the selection of the cluster-head follows the similar criteria as LEACH, but there are two major differences between O-LEACH and LEACH: (i) nodes of WSNs cannot be deployed in the DFS coverage area (first check) and (ii) the cluster-head and the node should be within the same WSN field if two WSNs cannot communicate with each other (i.e., checking in the flowchart).

For most applications, it would be better to assume that two WSN fields are isolated due to the following reasons: (i) saving information transfer energy since longer data transfer distance over the DFS terrain ends with higher energy consumption and (ii) wireless communication over the DFS area is not even allowed for some applications. However, we simulate the case that nodes inside different WSN fields can communicate with each other as well for reference. From the flow chart of the O-LEACH protocol, we have to admit the fact that the proposed protocol is only a fairly incremental modification to the original LEACH. The main point is to initiate the study about hybrid sensor networks with intriguing results.

### III. SIMULATION RESULTS

Based on the O-LEACH protocol, we simulate the network performance in terms of the node lifetime. In our simulation model: 1) most of parameters (e.g., probability of a node to become cluster head, data packet length, control packet length, etc.) are as same as other LEACH-based simulation models (listed in Table I) [5]–[7]; 2) the position of the sink in the LEACH model can be put in different places, while in our LEACH and O-LEACH ones, we put the sink of all the cases to the same position, i.e., in the middle of one edge of the sensor field (i.e., the centre of one end of the DFS), although later in the rectangular topology, we add a series of sinks to cover much longer distances with more evenly distributed energy consumption; 3) as the network energy dissipation is a totally statistical behaviour due to the random distribution of WSN nodes, we simulate every case for 1000 independent iterations (it takes days to get such statistical results); and 4) as the ONS

![Flowchart of the O-LEACH protocol.](image-url)
(DFS) is totally active (i.e., no energy constraint), the lifetime of the DFS is not considered. First, we compare the network performance in terms of the lifetime. Three cases are simulated: original LEACH without DFS; O-LEACH with varying the width of DFS coverage area (D) that two WSNs either can or cannot communicate with each other. As people use different parameters to evaluate the lifetime, i.e., the round number corresponding to the appearance of the first dead node, half of dead nodes or the last survival node (called as “first-dead,” “half-dead,” and “fully-dead” in the following part of the paper), we obtain all three parameters and find that network improvement may end with quite different results through these parameters. A node is considered to be dead if the remaining energy is zero [5], although reduced communication reliability may happen during the energy depletion. Note that in most practical applications, the DFS coverage is very specific and cannot be freely varied. While sometimes parallel DFS links may be deployed to cover more broad areas, therefore, the DFS coverage width is varied in our simulation for the purpose of comparison and possible reference.

<table>
<thead>
<tr>
<th>Table 1: Parameters Used in Simulation of O-LEACH [5]</th>
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<tr>
<td>Dimension of sensor field (a.u.)</td>
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<tr>
<td>Probability to be cluster head</td>
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<tr>
<td>Data packet length</td>
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<td>Control packet length</td>
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<td>Initial energy (J)</td>
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<td>Energy dissipation of one Tx (J)</td>
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<td>Energy dissipation of one Rx (J)</td>
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<td>Energy loss - free space (J)</td>
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<td>Energy loss - multipass fading (J)</td>
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<td>Data aggregation energy (J)</td>
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Fig. 3. Simulation results of network performance in terms of lifetime (roundnumber) using O-LEACH protocol. (a) TwoWSNs can communicate with eachother. (b) Two WSNs are isolated. (c) Typical lifetime evolution curves.

For the LEACH case, we obtain the average round number corresponding to “first-dead,” “half-dead,” and “fully-dead” are 731, 915, and 1741, respectively. Fig. 3(a) and (b) show the average lifetime evaluated by three “-dead” parameters for situations that the two WSNs can and cannot communicate with each other as we vary the value of D (from 5 to 50). We can see that: 1) The network performance in terms of lifetime keeps almost constant regardless the width of DFS coverage. 2) In the case that two WSNs cannot communicate with each other, nodes can save energy on broadcasting over smaller area (i.e., shorter distance), therefore, the average lifetime corresponding to either “first-dead” or “half-dead” is improved % compared to the case that two WSNs are connected (the average round number from 731 to 903 and from 915 to 1086 for “first-dead” and “half-dead”, respectively), while the last node’s lifetime (“fully-dead”) is more than doubled. 3) Compared to the conventional LEACH protocol, the improvement of O-LEACH if two WSNs can communicate with each other is very limited (% and % in
terms of “first-dead” and “fully-dead,” respectively. In fact, such improvement is simply converged to the original LEACH case if we further reduce the coverage percentage, i.e., %. Therefore, it is expected and mostly required for such hybrid sensor networks to employ O-LEACH with two WSNs isolated. Furthermore, typical lifetime evolutions are compared as well in Fig. 3(c), where D equals 20. These curves are specially chosen from thousands of simulated iterations with performance close to average ones. Results of LEACH protocol are also included. A legitimate question for above network model is how close to the reality of the hybrid sensor network in terms of the coverage of DFS and WSN. As mentioned in the introduction section, the distance of typical DFS link can vary from hundreds of meters to tens of kilometers, while the coverage diameter of WSN node is tens of meters. Therefore, it would be interesting to look into the case that the length of DFS link increases and the number of WSN nodes increases proportionally (to keep the approximate density).

Fig. 4. Normalized lifetime as we increase the length of DFS link (number of WSN nodes are increased proportionally, the widths of the DFS coverage area and the whole sensor field are fixed).

Fig. 5. The topology incorporating distributed optical fiber sensors.

To keep straightforward but simple, we fix the width of the whole sensor field to 100 and the coverage percentage of DFS to 20% (i.e., D equals 20). Also, we only consider the case that two WSNs are isolated. Fig. 4 illustrates the trend of normalized lifetime performance with increasing link length of DFS. Thenormalization is done using the ratio of the “-dead” parameter to the total node number. It is obvious that 100 is the optimum number for WSN nodes with parameters listed in Table I. As the length of the DFS link increases, the lifetime reduces dramatically, especially the “first-dead” parameter. More wireless sinks are required for longer DFS links, and the performance evaluation of various optical wireless sensor network topologies are of great interest. More practically, the number of base stations(sinks) should be increased (or linked into series) to sustain the long rectangular sensor field. Therefore, as a more general topology, Fig. 5 shows such hybrid sensor networks that have potential to cover much more broad areas under certain guidelines: 1) cascade of multiple rectangular regions in which the base station location of WSN sensor node is (100, 150) and 2) the DFS is located in the monitor area with massive volume of data, harsh environment, and poor security (located in the
middle of the rectangular region for this paper) to link the rectangular region and the location of fiber’s base station is (0, 25). The DFS can cover a certain area as previously discussed, for example 10 m (vertical axis) to monitor the required (e.g., temperature, strain, etc.) information within the coverage area, and give the data back to the fiber base station (still located at the center of one end of the DFS and with no need to worry about its power consumption). For more general topology of the hybrid OSN (DFS) and WSN network, we modify the O-LEACH algorithm and simulate a rectangular sensor network region that is divided into four small regions (i.e., in Fig. 5). In the total area, we randomly scatter 100 nodes, e.g., the number of nodes in each region is 21, 29, 23, and 27, respectively. The DFS is located in the middle of the total rectangular region as usual. We assume that the nodes in the upper and the lower part of the optical region can communicate with each other, and the simulation results are shown in Fig. 6. We can see from Fig. 6 that the round numbers of the first dead node in the four regions are 663, 805, 779, and 698, respectively. The first 20% of nodes die slowly, but the remaining ones die rapidly in the total region. The results further demonstrate that the hybrid sensor network incorporating DFS with the O-LEACH protocol can evenly distribute the energy load among nodes, therefore prolong the overall lifetime of the network.

![Fig. 6. Performance (number of live nodes versus round) after introducing the DFS into the rectangular sensor area.](image)

### IV. CONCLUSION

We investigated a modified energy-efficient communication protocol, called O-LEACH, for wireless sensor networks that consist of DFS links and randomly scattered wireless sensor nodes. Survival round numbers of WSN nodes are simulated for various cases using different parameters. The lifetime of the situation that two WSNs are isolated is more than 20% better than that of the case where nodes inside two WSN fields are reachable to any live nodes within the whole sensor field. This can be a deployment guideline for such hybrid sensor networks.

### REFERENCES


