Adapting LEACH Algorithm for Underwater Wireless Sensor Networks

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*Abstract***— The design of routing protocols for both terrestrial and underwater wireless sensor networks (WSNs and UWSNs) presents several challenges. These challenges are mainly due to the specific characteristics (limited battery, limited processing power and limited storage) of this type of networks. However, saving energy consumption is a real challenge that should be considered. Clustering technique is one of the methods used to cut down on energy consumption in WSNs and UWSNs. It consists of dividing a network into subsets called clusters, where each cluster is formed of cluster head and nodes. Low Energy Algorithm Adaptive Clustering Hierarchy (LEACH) is the most popular protocol for clustering in WSNs. Using TDMA based MAC protocol, LEACH allows significant energy conservation by balancing energy consumption of network nodes. In this paper, we propose an approach based on LEACH algorithm for routing in Underwater Wireless Sensor Networks. The proposed approach profits of the advantages offered by LEACH algorithm for WSNs in terms of energy conservation. Simulation results show that the proposed approach can reduce the total energy consumption and prolong the network lifetime compared to the direct transmission.**

Keywords-Underwater Wireless Sensor Networks; Acoustic Communication; Clustering Algorithm; LEACH Algorithm; Energy Consumption.

I. INTRODUCTION

Oceans and seas comprise over 70% of the earth's surface. However, Underwater Wireless Sensor Networks (UWSNs) are deployed through different applications such as oceanographic data collection, pollution monitoring, undersea exploration, disaster prevention, assisted navigation, tactical surveillance and mine reconnaissance [1].

UWSNs are formed of miniaturized self-alimented entities called sensor nodes, which are interconnected using wireless acoustic links. In UWSNs, communications are established by acoustic waves, which allow a very well propagation through water and require much less power compared to the radio signal, which delivers very poor performance in underwater areas since it provides transmission ranges of only a few meters. A challenge in underwater acoustic communication is limited bandwidth caused by high absorption factor and attenuation, long propagation time, and the fading of the resulting signal, which should attract much interest. Another challenge is the sensor node failure due to environmental conditions.

One major problem related to the UWSNs is the energy conservation which the network lifetime depends on. Since UWSNs are deployed in harsh environment, it is often impossible to recharge or replace battery nodes after their exhaustion. However, the issue of energy conservation for these networks is to develop routing techniques which take into account the different problems of underwater communications such as: limited bandwidth, throughput, long propagation delay (high latency), high bit error rates and signal attenuation. Therefore, regarding the characteristics of underwater communications, UWSNs have recently motivated a growing interest in studying architectures and networking protocols.

In this paper, we propose an approach based on Low Energy Algorithm Adaptive Clustering Hierarchy (LEACH) [2] for Underwater Wireless Sensor Networks. The proposed approach is an adaptation of LEACH algorithm which is one of the most well-known energy efficient clustering algorithms used in terrestrial Wireless Sensor Networks. We implement this proposition on Matlab in order to perform experiments according to many parameters such as the network lifetime.

This paper is structured as follows: A brief introduction on underwater wireless sensor networks and the deal of these networks regarding their constraints and limits, particularly, in acoustic communications are given in Section I. Section II is dedicated to the related works that treat security issue and routing protocols used in UWSNs. In Section III, we present the proposed approach. In Section VI, we present simulation results. Finally, we summarize the main contribution of this study and we give indications on future works in Section V.

II. RELATED WORKS

In recent years Underwater Sensor Networks have attracted a significant interest of the scientific community. Thus, different works that address design issues related to the characteristics of these networks were introduced in the literature [3][4][5]. The energy resource limitation is an important issue that must be taken into consideration in order to maximize the network lifetime. Generally, routing collected data in the network affects directly the energy consumption. Another aspect related to the energy consumption and smooth functioning of UWSNs is the safety and security of these networks. Therefore, routing protocols must be designed from the beginning with the aim of efficient management of energy resources. Also the proposed security solutions must consider the energy conservation. In this section, we present some works which address the security of acoustic communications and some proposed routing protocols used in UWSNs.

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In [6], the authors introduced a novel approach to secure both unicast and multicast communications in underwater acoustic sensor networks. This approach provides confidentiality and message integrity.

Ming et al. [7] proposed a CLUster-based Secure Synchronization (CLUSS) protocol. It is based on the time synchronization for secure clusters formation. CLUSS is executed in three phases: the first phase consists of the authentication process, where each sensor nodes is authenticated to the cluster head which it belongs and the cluster heads are authenticated to beacons. In this phase, the identified malicious nodes will be removed from the network. The inter-cluster synchronization phase corresponds to the synchronization between cluster heads and beacons. The intra-cluster synchronization phase is where ordinary nodes synchronize themselves with cluster heads. The performance evaluation demonstrates that CLUSS can reduce the number of transmitted packets. Thus, it allows saving energy consumption in the network.

A Cluster based Key management Protocol (CKP) was proposed in [8]. CKP is a new key management protocol for clustering hierarchical networks, used to secure communication inside and outside a cluster. CKP operates in four phase: Key generation and distribution phase, Cluster setup phase, Data gathering phase, Data forwarding phase. Simulation results show that the CKP is energy and storage efficient.

In [9], the authors proposed a k-means based clustering and energy aware routing algorithm, named KEAR for underwater wireless sensor networks that aim to maximize the networks lifetime. The proposed algorithm is based on two phases: cluster head (CH) election and data transmission. In the CH election phase, the election of the new cluster heads is done locally in each cluster based on the residual energy of each node. In the data transmission phase, sensing and data transmission from each sensor node to their cluster head is performed, where the cluster heads in turn aggregate and send the sensed data to the base station.

Carmen et al. [10] proposed a distributed energy aware routing protocol called Distributed Underwater Clustering Scheme (DUCS), which is based on clustering techniques and supports energy consumption. In DUCS, firstly, the network is divided into clusters, where each cluster head is selected through a randomized rotation among different nodes in order to allow equitable energy dissipation between nodes in the network. Secondly, to reduce the amount of transmitted data to the base station, the cluster heads aggregate the collected data by the member nodes that belong to their own cluster, and send an aggregated packet to the sink. While this algorithm is efficient, it presents some limitations regarding the nodes mobility, which is not considered. However, it can affect the structure of clusters. Also, exchanged data between CHs can be interrupted in the case where ocean currents move the cluster heads [11].

Seah et al. [12] introduced a hierarchical clustering routing protocol architecture called Multipath Virtual Sink (MVS). In MVS, CHs use many local aggregation points which are connected to local sinks. Using a high-speed communication channels, local sinks are linked to each other through multiple paths.

In [13], the authors proposed a distributed Minimum-Cost Clustering Protocol (MCCP), where clusters are selected by considering the total energy consumption of the cluster, the residual energy of the cluster head and cluster members and the distance between the cluster head and the underwater sink. Firstly, all sensor nodes are candidate to be cluster heads (CHs) and cluster members. In order to form a cluster, each candidate constructs its neighbor set and uncovers neighbor set. Secondly, the average cost of that particular cluster is calculated, and the one with the minimum average cost is selected as a cluster head. We note that the cost of a cluster represents both energy consumptions: to send the packet from a member to the CH and from CH to the base station. Finally, an ”INVITE” message is sent by selected CH, to all the other cluster nodes to become its cluster’s member, otherwise, it sends a ”JOIN” message to the specific cluster head. We note that MCCP protocol improves the energy efficiency and prolong the lifetime of the network.

III. PROPOSED APPROACH

The hierarchical routing based on clustering is a very efficient technique used to resolve the problem of energy consumption in both WSNs and UWSNs. Thus, the goal of clustering is to extend the lifetime of a network by providing a good load balancing. In the following, we present proposed approach, which consists in integrating into the LEACH algorithm, the energy model used in submarine networks for data transmission. Firstly, we introduce LEACH algorithm, which is a hierarchical routing protocol most widely used in wireless sensor networks (WSN). Secondly, we present the energy models used for data transmission in both WSNs and UWSNs. Finally, we substitute the energy model associated to LEACH algorithm and used in terrestrial sensor networks, by the energy model dedicated to the acoustic communications and through numerical results obtained by simulations, we show the behavior of this algorithm in term of energy conservation.

A. LEACH Functioning

LEACH is a dynamic clustering algorithm which uses a randomized periodical rotation of cluster heads among the nodes in order to distribute equitably the energy load between sensor nodes in the network. Thus, all nodes have the same probability to be elected cluster head. However, the CH election is updated in each iteration. LEACH is divided into rounds. Each round consists of two phases: Set-up phase, where cluster heads are elected and clusters are formed; Steady-state phase, where the data are transferred to the sink node.

In set-up phase, the electing process is started by considering a percentage “P”, which is the desired percentage of cluster heads for a given round. Each node “i” chooses a random number between 0 and 1. If the number is less than a threshold T(i), the node declares a cluster head for the current round. The CHs inform their neighbors of their election and each remaining node decides to choose the closest CH.

In steady-state phase, the CHs receive sensed data from cluster members, and transfer the aggregated data to the BS. Thus, using the Time Division Multiple Access protocol (TDMA, which, is used to ensure transmission packages within collision and less costly in energy) [2], each node send its collected data to CH at once per frame allocated to it. After this transmission, the nodes cut off its transmission and goes to sleep mode until next allocated transmission slot.

1. Detailed principle

Let P be the average desired percentage of clusters in our network at an instant “t”. LEACH is composed of cycles made of $\frac{1}{p}$ rounds.

Each round “r” is organized as follows:

1) Each node “i”:
   - computes the threshold T(i) such as:

$$T(i) = \begin{cases} \frac{p}{1-P*\left(r mod \frac{1}{P}\right)} & \text{if i has not been CH yet} \\ 0 & \text{if i has already been CH} \end{cases}$$

   - chooses a pseudo-random number $0 \leq x_i \leq 1$.
   - If $x_i \leq T(i)$ then “i” designates itself as a CH for the current round. T(i) is computed in such as every node becomes CH once in every cycle of $\frac{1}{p}$ rounds we have T(i) = 1, when $r = \frac{1}{p} - 1$.
2) The self-designed CH informs the other nodes by broadcasting an advertisement message with the same transmitting power (using carrier sense multiple access, CSMA MAC).
3) Based on the received signal strength of the advertisement message, the rest of nodes choose its CH for the current round. Thus, they send a message back to inform the considered CH (using the same protocol as in the last step, CSMA MAC).
4) CHs set up a “transmission schedule” based on Time Division Multiple Access) to the nodes that joined their clusters. They inform each node at what time they transmit its data.
5) CHs keep listening for the results. Normal sensors get measures from their environment and send their data. When it is not their turn to send, they stay in sleep mode to save energy (Collisions between the transmissions of the nodes from different clusters are limited thanks to the use of code division multiple access (CDMA) protocol).
6) CHs aggregate, and possibly compress the received data and send it to the base station in a single transmission. This transmission may be direct, or multi-hopped, if it is relayed by other CHs.
7) Steps 5 and 6 are repeated until the last round.

LEACH can be extended such as LEACH-C introduced in [14]. Thus, in LEACH-C, the location information and the residual energy value of the nodes are considered as additional parameters for the computation of the T(i).

Since each node decides whether to designate itself as a CH or not, without considering the behavior of surrounding nodes. Therefore, for a given round, a number of CHs can be very different from the selected percentage “P”. Also, all the elected CHs may be located in the same region of the network, leaving “uncovered” areas. For this reason, In that case, one can only hope that the spatial repartition will be better during the next round.

B. Energy model

A sensor consumes energy to perform three actions: acquisition, communication and data processing. The energy consumed to perform data acquisition and processing operations is not very significant compared to the energy used for communications. However, communications consume much more energy than other tasks. They cover communications in transmission and reception.

The radio model of energy consumption in terrestrial sensor networks associated to LEACH algorithm and proposed by Heinzelman et al. in [2] is defined as follows:
The energy to emit ETx (k, d) and receive ERx (k) data are given by:

- To emit k-bit through a distance ”d”, the transmitter consumes:
  - ✓ ETx(k, d) = ETxelec(k) + ETxamp(k, d)
  - ✓ $ETx(k, d) = (E_{elec} * k) + (E_{amp} * k * d^2)$
- To receive k-bit message, the receiver consumes:
  - ✓ ERx(k) = ERxelec(k)
  - ✓ ERx(k) = k * Eelec

E_{elec} and E_{amp} represent respectively the energy of electronic transmission and amplification.

Usually, acoustic communications are used in UWSNs. We use the same energy model as introduced in [15], which was proposed for underwater acoustic networks. According to this model, to achieve a power level P_0 at a receiver at a distance “d”, the transmitter power Etx(d) is :

$$Etx(d) = P_0\, d^2\, (10^{\alpha(f)/10})^d \qquad (1)$$

where $\infty(f)$, is the absorption coefficient depending on the frequency range under given water temperature and salinity. $\infty(f)$ is measured in dB/m and is used for frequencies above a few hundred KHz can be expressed empirically using Thorp’s formula introduced in [16].

$$\alpha(f) = 0.11 * \frac{10^{-3}*f^2}{1+f^2} + 44 * \frac{10^{-2}*f^2}{4100+f^2} + 2.75x10^{-2} * f^2 + 3 * 10^{-6} \qquad (2)$$

where “f“ is the carrier frequency for transmission in KHz. The reception power is assumed to 1/3th of the transmission power.

After having presented the functioning of LEACH and its conventional energy model used in WSNs, we adapt the use of LEACH in UWSNs by associating the energy model (see the formula 1) dedicated to acoustic communications and the technical analysis of the proposed approach is presented in the next section.

IV EXPERIMENTAL RESULTS

In order to evaluate proposed approach and show the interest of using LEACH algorithm in underwater sensor networks, we have done simulation by considering an underwater sensor network based on a static 2D architecture type, where the underwater sensor nodes are deployed and anchored to the bottom of the ocean. Underwater sensors may be organized in a cluster-based architecture, and be interconnected to one or more head sensors (underwater gateways) by means of wireless acoustic communication.

The head sensors are network devices that transmit data from the bottom of the ocean network to a surface station [17] (see Fig. 1). Firstly, we implemented LEACH algorithm with the energy model (presented in formula 1) used to transmit data in UWSNs. Simulations are done using Matlab, by considering parameters given in Table 1 and the following assumptions:

- Sensor nodes and the underwater sink are stationary.
- All sensors nodes are homogeneous and have the same initial energy.
- The underwater sink has no limitation in terms of energy, processing and memory.
- The sensors performed periodical measurements at fixed intervals.

Secondly, by considering the lifetime and residual energy, we compare the proposed approach (data is transmitted to the underwater sink via elected cluster head sensors) to the direct communication approach (each underwater sensor transmits directly its data to the underwater sink).

TABLE I. SIMULATION PARAMETERS

Parameter	***Value***
Field Dimension x, y, maximum (Network size)	50m, 50m
Number of Nodes	100
Optimal Election Probability of Cluster Heads (percentage of desired clusters)	5
Power level P_0 at a receiver	$0{,}1 * 10^{-7}$
Initial Energy	5J
Frequency of carrier acoustic signal	25KHZ
Rounds (Time)	200

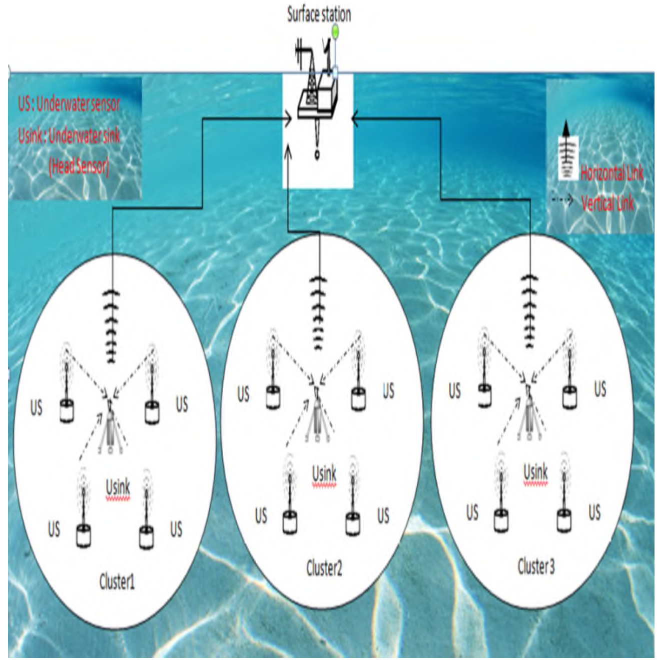

Figure 1. Network Model

Fig. 2 shows the residual energy in the network. We note that using direct communication, the residual energy in the network decreases quickly and reaches 0 values at rounds 175. Compared to LEACH algorithm, the residual energy decreases progressively and it equal to 150 J at rounds 200. However, due to the clustering approach applied on the network, LEACH algorithm retains more energy comparing to the direct communication.

Regarding the histogram in Fig. 3, we note that after 50 rounds, using direct communication algorithm, the first 21 nodes are dead, while, compared to the LEACH algorithm, there is no dead node. After 100 rounds, in direct communication algorithm, we observed that 61 nodes are dead, while in LEACH algorithm the number of dead nodes is 37. Also, after 150 rounds, we note that the number of dead nodes is very important in direct communication compared to LEACH algorithm. At the end of the simulation, all nodes are dead in direct communication, while 21 nodes remain alive in LEACH algorithm. Therefore, in this set of simulations, we note that LEACH is about 21% more efficient in terms of network lifetime compared to the direct communication.

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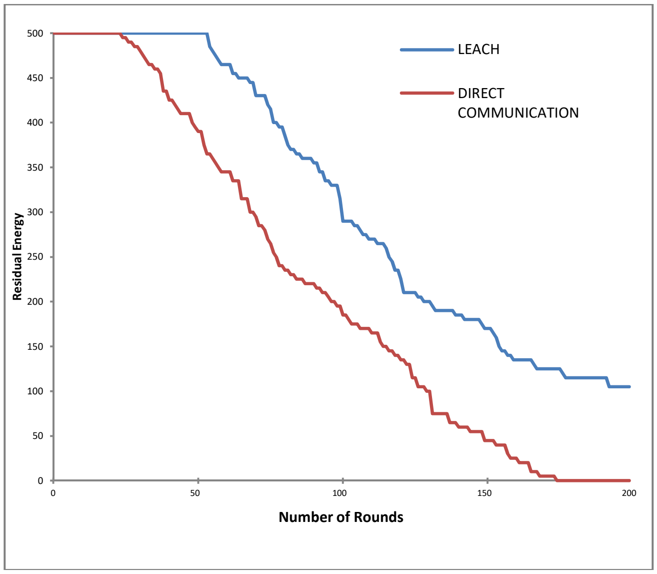

Figure 2. Residual energy vs. Number of rounds

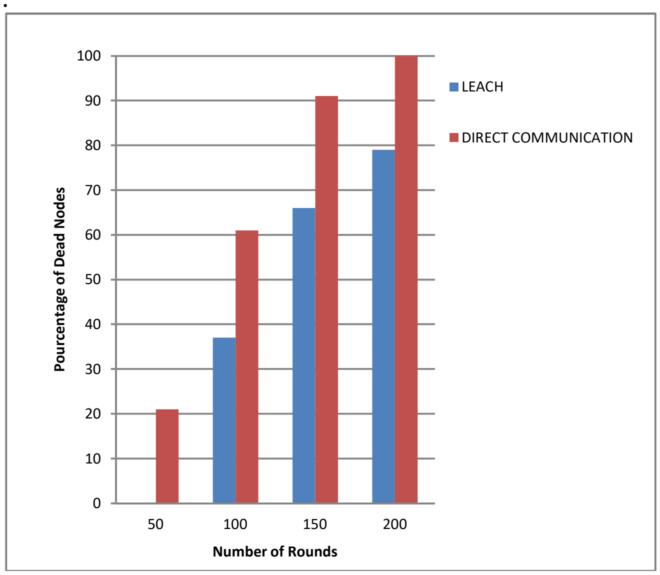

Figure 3. Percentage of dead nodes

V. CONCLUSION

In both underwater and terrestrial sensor networks, each node is powered by a limited energy source. However, energy conservation is an important issue that must be taken into consideration in order to build mechanisms that allow users to extend the lifetime of the entire networks. LEACH algorithm is one of the most well-known energy efficient clustering algorithms for WSNs. In order to profit of advantages provided by LEACH algorithm in WSNs, we propose in this paper an adaptation of LEACH algorithm for underwater acoustic sensor networks. Our proposition considers the residual energy in the cluster head selection and uses an energy consumption model dedicated to acoustic communications. The experimental results show that compared to the direct communication proposed approach can effectively reduce the energy consumption and extend the networks lifetime. As a future works, we will compare proposed approach to other clustering protocol used in underwater sensor networks and improve it by considering, other parameters such as data rate, throughput, and propagation delay.

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