A Cross-Layer Approach to Maximize the Lifetime of Underwater Wireless Sensor Networks

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Abstract. Efficient usage energy of sensors can lead to prolonged lifetime in underwater wireless sensor networks (UWSNs). This paper addresses maximization of the network lifetime for UWSNs. More specifically, it considers an optimal cross-layer design of transmission schemes. Here we restrict ourselves to the type of time division multiple access schedules in the link layer. In order to balance energy consumption over different nodes, we develop a Mixed Integer Non-Linear Programming formulation to facilitate joint optimization of link schedules, transmission powers and rates of sensors. We have also conducted extensive network simulations to test the proposed algorithm. The results confirm that our approach can prolong overall network lifetime.

Keywords: Cross-layer design · Network lifetime · Underwater wireless sensor networks

1 Introduction

Underwater Wireless Sensor Networks (UWSNs) are self-organized systems in which a number of sensors collect and relay useful data in harsh underwater environments. UWSNs are various and promising, including monitoring different areas for security surveillance, monitoring pollution and oil extraction etc. [1,8]. Methods developed for terrestrial wireless sensor networks to maximize their lifetime perform poorly in UWSNs. One of the reasons is that UWSNs usually communicate via underwater acoustic channels with consideration of the properties of underwater environments [2]. Available energy of sensors in UWSNs are limited due to the failure of replacing the batteries of sensors, and unreasonable use of the limited energy may cause a short network lifetime in UWSNs.

The underwater acoustic channels are well studied in [7]. Based on this kind of researches, methods which economize on energy for UWSNs were proposed. Jornet et al. [3] proposed a focused-beam routing (FBR) protocol that determined the most energy-efficient candidates for nodes relaying data. Yan et al. [9]

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proposed an energy efficient routing based on nodes' depth information. Rhdoplu et al. [5] proposed an energy optimized MAC protocol. Ponnavaikko et al. [4] focused on computing energy-efficient TDMA-based routes for delay-constrained UWSNs. While they all enjoy high energy efficiency, however, they fail to take the energy balance of nodes into account so that some special nodes with heavy data load might quickly drain their energy in these methods. As a result, the performance in terms of network lifetime are severely compromised.

In our method, we first restrict the link schedules to the type of time division multiple access (TDMA) schedules, so as to eliminate the communication interference among nodes. Then, with considering constraints of nodes and underwater acoustic channels, we define an optimal problem whose objective is to maximize the network lifetime. We find that the optimal problem is a Mixed Integer Non-Linear Programming (MINLP). Finally, we propose the iterative algorithm named network lifetime maximization algorithm which alternates adjusting TDMA schedules and computation of optimal transmission rates and powers of nodes under a fixed TDMA schedule.

2 Problem Formulation and Network Lifetime Maximization Algorithm

In this section, we formulate an optimization problem, the objective of which is to maximize the network lifetime for UWSNs. Moreover, we restrict the link schedules to be some kind of TDMA schedules, and propose an iterative algorithm which optimizes the transmission scheme for network lifetime maximization.

2.1 Optimization Objective: Network Lifetime

We consider UWSNs which consist of a number of common nodes (CN) and one sink node. Common nodes are deployed underwater and measure the environmental parameters at a fixed source rate. Let T_i be the lifetime of common node i, *i.e.*, the time span from its deployment to the time it drains its energy, then the network lifetime T_{total} is defined as $T_{total} = min_{i \in I} T_i$, where I represents the set of common nodes. The objective of our design is to maximize the network lifetime T_{total},

$$max\ T_{total} = max\ min_{i \in I} T_i, \tag{1}$$

subject to the following constrains that are used to balance the energy consumption among different nodes.

Flow Conservation. During a TDMA cycle period, for each common node (CN) in the network, the transmitted data should be equal to the sum of received data and sensed data, which could be formulated as:

$$\sum_{n \in Send} x_i^n - \sum_{n \in Receive} x_i^n = N \cdot s_i \cdot T_{slot}, \tag{2}$$

where x_i^n is the transmitted bits or received bits of the *i-th* node in the *n-th* time slot. *Send* is the set of allocated time slots for the *i-th* node transmitting data, and *Receive* is the set of time slots for the *i-th* node receiving data. N is the total amount of time slots during a TDMA period. s_i represents the source rate of the *i-th* node, i.e., the constant rate of collecting environmental information in bit per second. Both x_i^n and s_i are positive numbers. T_{slot} is the time length of a TDMA time slot. The transmission time $T_{transmit}$ and the propagation time $T_{propagate}$ should be included in a time slot T_{slot}. Let the transmission rate of the *i-th* node in the *n-th* time slot be R_i^n. Then, x_i^n can be expressed as:

$$x_i^n = R_i^n \cdot T_{transmit}. \tag{3}$$

Energy Conservation. During the network lifetime, energy consumption of each node should be equal to or less than the initial energy $E_{initial}$ stored in the battery before deployment. We neglect $E_{receive}$ and E_{sense} in our design because $E_{transmit}$ is often 100 times more than both of them [6]. $E_{transmit}$ is computed as the product of the average energy consumption during a TDMA period and the total amount (we assume that it is p) of available TDMA periods during the network lifetime. Then we have:

$$E_{initial} \geq E_{average\_TDMA} \cdot p = \frac{\sum_{n \in Send} P_{transmit,i}^n \cdot T_{transmit}}{N \cdot T_{slot}} \cdot T_{total}, \tag{4}$$

where $P_{transmit,i}^n$ is the transmission power of the *i-th* node in the *n-th* time slot. In this paper, the 3dB bandwidth $B_{3dB}(l)$ is used. And we assume the transmitted signal p.s.d. $S(f)$ is flat, *i.e.*, $S(f) = S_l$ for frequencies within the range of $B_{3dB}(l)$ and 0 otherwise, which is also appropriate in practice. Then, we have:

$$P_{transmit,i}^n(l) = \int_{B_{3dB}(l)} S(f)df = B_{3dB}(l) \cdot S_l. \tag{5}$$

Rate Constraints. According to the information theory, the transmission rate of a node at any time should be equal to or less than the available channel capacity C:

$$\begin{aligned} R_i^n \leq C &\approx \int_{B_{3dB}(l)} \log_2\left(\frac{P_{transmit,i}^n(l)/A(l,f)}{N(f) \cdot B_{3dB}(l)}\right)df \\ &= B_{3dB}(l) \cdot \log_2 P_{transmit,i}^n(l) - \lambda(l) \end{aligned} \tag{6}$$

where $\lambda(l)$ is defined as: $\lambda(l) = \int_{B_{3dB}(l)} log_2[A(l,f)N(f)B_{3dB}(l)]df$. We assume that the channel capacity in each transmission process can be adequately used, *i.e.*, R_i^n is equal to C in each transmission, then we have:

$$R_i^n = B_{3dB}(l) \cdot \log_2 P_{transmit,i}^n(l) - \lambda(l) \tag{7}$$

The transmission power $P_{transmit,i}^n$ should be less than the maximum transmission power P_{max} determined by the sensor's hardware.

With the consideration of aforementioned constraints, we can formulate the optimization problem. Let $q_i = 1/T_i$ and $q = 1/T_{total}$. Then the optimization problem Eq. (1) can be re-formulated as the following equivalent:

$$\begin{aligned} & min.\ q \\ & s.t.\ (\sum_{n \in Send} R_i^n - \sum_{n \in Receive} R_i^n) \cdot T_{transmit} = N \cdot s_i \cdot T_{slot} \\ & \quad q_i N T_{slot} E_{initial} \geq \sum_{n \in Send} 2^{\frac{R_i^n + \lambda(l)}{B_{3dB}(l)}} \cdot T_{transmit} \\ & \quad q = max_{i \in I}\ q_i \\ & \quad P_{transmit,i}^n \leq P_{max} \end{aligned} \tag{8}$$

The optimization problem is formulated as a Mixed Integer Non-Linear Programming (MINLP). Variables in this optimal problem are TDMA schedules and transmission rates (and powers) of nodes for a fixed TDMA schedule.

2.2 Network Lifetime Maximization Algorithm

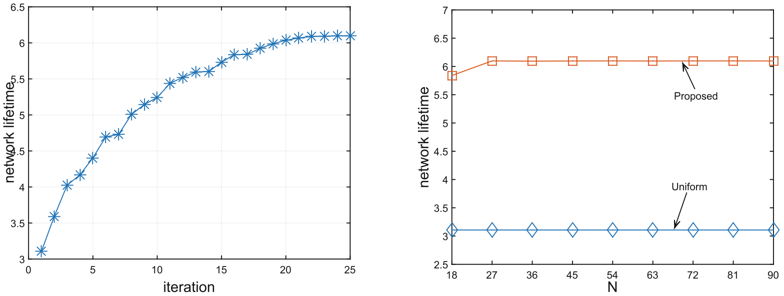
In this subsection, a transmission scheme optimizing algorithm which maximizes the network lifetime for UWSNs is proposed. The algorithm alternately adjusts the TDMA schedules and computation of the optimal transmission powers and rates of nodes in all time slots for a fixed TDMA schedules. Steps of the proposed algorithm are shown as follow:

(1) Initialize from a transmission scheme with an uniform TDMA schedule where all links are allocated with the same number of time slots. Common nodes transmit data in allocated slots, and receive data or idle in other slots.
(2) Compute the optimal transmission powers and rates of nodes under the TDMA schedule in this iteration by solving the optimal problem. Compare the calculated q value in this iteration with q value at the last iteration. If q in this iteration is decreased, turn to (3), otherwise, turn to (4).
(3) Update the TDMA schedule. When we adjust the TDMA schedule without changing data load of nodes which is calculated in the step (2), if the q value of the network decreases, the adjusted TDMA schedule is feasible for the next iteration. The adjusted TDMA schedule is regarded as the TDMA schedule in the next iteration.
(4) The transmission scheme in the last iteration is regard as the optimal transmission scheme for the network.

3 Simulation Results

3.1 Simulation Setup

Here, we will compare the performance of our algorithm with that of transmission scheme with an uniform TDMA schedule. We simulate in a linear topology, in which common nodes $CN = \{CN_1, CN_2, \ldots, CN_M\}$ and a sink are deployed in a line, and the geographic distance between adjacent nodes l is a constant. We avoid the transmission loop problem by restricting that each node only selects nodes nearer to the sink as its next hops. For each node, we assume that it transmits data by hops and only its adjacent nodes are in its communication range.



(a) (b)

Fig. 1. Network lifetime with varying N. (a) Network lifetime in each iteration when $N = 90$, (b) comparison of our algorithm with transmission schemes with an uniform TDMA schedule under different N

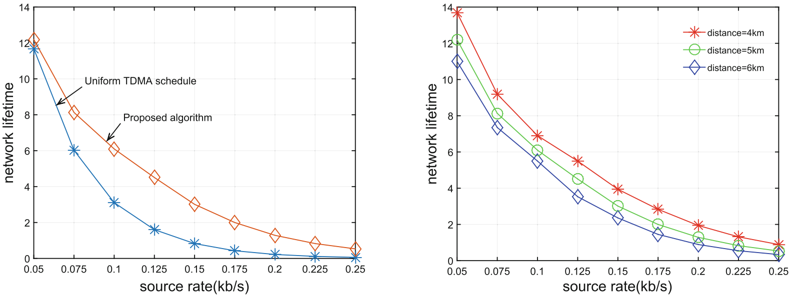
3.2 Numerical Results

We first simulate with $M = 9$, $L = 5\,\text{km}$, $s_i = 0.10\,\text{kb/s}$, $N = 90$ and $T_{slot} = 5\,\text{s}$. Figure 1(a) shows that, when $N = 90$, the network lifetime roughly converges after 20 iterations.

Figure 1(b) shows the network lifetime achieved by our proposed algorithm and transmission schemes with an uniform TDMA schedule under different numbers of nodes. Note that the network lifetime achieved by the proposed algorithm when $N = 18$ is a little lower than those of other values of N. The reason is that, when $N = 18$, the most energy-consumption nodes still have potential to raise its lifetime even if the network is under the optimal transmission schedule. In other words, when the number of time slot is small, it not enough for the network to allocate an appropriate number of time slots to the most energy-consumption node, thus resulting in the reduction of the network lifetime.

Figure 2(a) shows the network lifetime achieved by our algorithm and transmission schemes with an uniform TDMA schedule under different s_i (ranges from $0.05\,\text{kb/s}$ to $0.25\,\text{kb/s}$) in the linear topology when $N = 27$. The network lifetime decreases with the source rate increasing because of the increasing data load in the network. The results show that our algorithm outperforms transmission schemes with an uniform TDMA schedule.

Figure 2(b) shows how the maximal network lifetime achieved by our algorithm changes with L under different s_i. We set $N = 27$, and L are respectively 4 km, 5 km and 6 km. We find that the network lifetime decreases with L increasing.



(a) (b)

Fig. 2. Network lifetime achieved by varying different parameters. (a) varying s_i, (b) varying l.

4 Conclusion

We consider a cross-layer approach to maximize the network lifetime for energy-constrained UWSNs. An optimization problem is defined when we restrict the link schedules to be the kind of TDMA schedules, which is formulated as a mixed integer non-linear programming. Then, the algorithm is proposed to solve the optimal problem. Simulation results show that our algorithm constantly outperforms transmission schemes with an uniform TDMA schedule.

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