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Cross-Layer Energy Minimization for Underwater ALOHA Networks

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***Abstract*—Underwater networks suffer from energy efficiency challenges due to difficulties in recharging underwater nodes. In addition, underwater acoustic networks show unique transmission characteristics such as frequency-dependent attenuation, which causes the transmission power to significantly depend on the bandwidth and the distance. We here investigate the cross-layer energy minimization problem in underwater ALOHA networks considering the unique transmission properties of the underwater medium. We first analyze the separate optimization of the physical (PHY) and multiple access control (MAC) layers to minimize energy consumption. We analytically obtain the energy-optimum channel access rate for the ALOHA MAC layer, which minimizes the energy consumption per successfully transmitted bit. We then formulate a cross-layer optimization problem, which jointly optimizes PHY and MAC layers to minimize energy consumption. We show that such cross-layer optimization reduces the energy consumption per bit as much as 66% in comparison with separate optimization of both layers. Cross-layer optimization achieves this energy efficiency by assigning higher MAC-layer resources to the nodes that have a longer distance to the base station, i.e., which experience a less efficient PHY layer. Moreover, cross-layer optimization significantly increases the amount data transferred until first node failure since it results in a more homogeneous energy consumption distribution among the nodes.**

***Index Terms*—ALOHA, cross-layer design, multiple access control (MAC), underwater networks.**

I. Introduction

UNDERWATER networks suffer from energy efficiency challenges since it is very difficult to recharge the underwater nodes if they have limited power supply. Energy consumed during communication is a major component of the overall energy consumption of an underwater node; hence, energy efficiency is an important consideration in designing underwater communication protocols.

Underwater networks pose many challenges from a communications point of view due to the unique characteristics of the medium. Two of the major issues with the underwater acoustic channel is the large propagation delay and the frequency-dependent attenuation. Large propagation delay makes the multiple access control (MAC) of underwater channels problematic by reducing the applicability of commonly used methods such as centralized access control and time slotting. Thus, one of the most feasible MAC methods is to use a distributed random access MAC such as ALOHA [1].

Along with the large propagation delay, frequency-dependent attenuation causes energy expenditure to be significantly dependent on both distance and bandwidth [2]. Due to these unique properties of the underwater acoustic medium, a systems-level approach is required to address the energy efficiency challenges of underwater nodes. An isolated view of communication layers may result in suboptimal results, which may degrade the overall energy efficiency of an underwater communications system. For that reason, we here investigate the cross-layer optimization of random access MAC layer and the physical (PHY) layer of an underwater network to minimize the overall energy consumption.

In an underwater random access network, both MAC and PHY layers influence the goodput of a node: In the MAC layer, a node's goodput can be increased by selecting a higher channel access rate, i.e., by giving the node an advantage over other users by increasing its channel capture probability. In the PHY layer, it is possible to increase goodput by increasing the transmission power, which, in turn, increases the channel capacity. We here investigate a cross-layer optimization of these layers to minimize the energy consumption per bit.

As a benchmark policy, we first investigate the isolated optimization of the ALOHA MAC layer and the underwater PHY layer. For the MAC layer, we obtain the energy-optimum channel access rate, which minimizes the energy consumption due to the MAC layer. We also obtain the channel access rate, which maximizes MAC-layer utilization. Then, we separately optimize the underwater PHY layer to minimize the energy consumption.

We then propose a cross-layer approach and jointly optimize the PHY-layer transmission power and the MAC-layer channel access rate. Our results show that the nodes, which are farther away from the base station, should be assigned a higher channel access rate in the MAC layer and should be assigned a lower transmission capacity in the PHY layer because distant nodes have less energy efficient PHY layers in comparison with closer nodes. Since the nodes farther away from the base station consume more energy while transmitting, they should increase their MAC-layer channel access rate to increase their share in the channel goodput.

We evaluate the performance of cross-layer and separate-layer policies for both a large-scale network with a 100-km

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radius and a small-scale network with a 10-km radius. Numerical results show that the cross-layer optimization outperforms the separate optimization of both layers by reducing the energy consumption per bit up to 66% for a large-scale network and 7% for a small-scale network. Cross-layer optimization is more crucial for large-scale networks due to the high transmission power requirements for networks covering large distances.

In addition to the significant improvement in energy consumption, cross-layer optimization results in a more homogeneous energy consumption distribution among the nodes. Such a homogeneous distribution significantly increases the amount data transferred until the first node failure due to battery drain up. In contrast, separate optimization of layers results in the assignment of very high transmission powers to distant nodes, which degrade their lifetime significantly.

To the best of our knowledge, this is the first attempt to evaluate the energy efficiency of an underwater ALOHA network.

The rest of this paper is organized as follows. In the next section, we survey the relevant literature. In Section III, the system model is described. Separate optimization of PHY and MAC layers is investigated in Section IV, and cross-layer optimization is analyzed in Section V. We present the numerical results in Section VI and the conclusions in Section VII.

II. Related Work

ALOHA protocol is one of the oldest multiple access protocols for terrestrial networks [3]. Due to its simplicity and due to the difficulties in the underwater medium such as the large propagation delay experienced by acoustic waves, ALOHA is one of the most commonly studied underwater MAC protocols. Its performance for underwater networks has been investigated in several studies [1], [4] and in real sea experiments [5]. In contrast to terrestrial networks, slotted ALOHA operation does not yield performance gains for underwater networks in comparison with pure ALOHA due to high propagation delay [6]. There are several proposals for improving time slotting for ALOHA [7]–[10], but here we investigate the performance of pure ALOHA since global synchronization may not be feasible for underwater networks. We also do not consider Request-to-send (RTS)/Clear-to-send (CTS) exchange as the effect of long preambles in underwater communication reduces their efficiency [11], [12], although there are studies that consider hand shaking for underwater networks [13].

Performance of ALOHA is also investigated for multihop networks and single-hop networks. Performance analysis of ALOHA for multihop networks is studied in [14]. A modified analytical model of ALOHA in a string multihop network is presented in [15].

Energy efficiency of underwater networks has been also investigated, but this paper is the first attempt to model the energy efficiency of ALOHA. In [16], the authors proposed a duty cycling protocol for underwater sensor networks. A reservation-based energy-efficient MAC protocol is proposed in [17], and a code-division-multiple-access-based energy-efficient protocol is proposed in [18]. Another MAC protocol, which uses tone-based contention resolution, is proposed in [19]. Joint consideration of random access with compressed sensing is proposed in [20] to improve energy efficiency in underwater sensor networks.

TABLE I
Model Parameters Given in [24] for Transmission Power

Case	α_1	α_2	α_3	β_1	β_2	β_3
1	-0.00235	0.01565	2.1329	0.014798	1.0148	74.175
2	-5.617e-5	0.02855	2.9305	0.04317	0.90597	76.156

The relationship between acoustic link capacity and distance is first modeled in [2], which presents the optimal transmission power and bandwidth to achieve a desired signal-to-noise ratio. This model has been used for joint frequency selection and relay placement for energy efficiency in [21], for joint frequency and power allocation in [22], and for energy-efficient routing in [23]. An approximate model based on [2] is proposed in [24], which gives the optimal transmission power as a convex function of capacity and distance. We here use this model to investigate the joint selection of MAC-layer channel access rate of the ALOHA protocol and the PHY-layer capacity.

III. Scenario Description and Definitions

We consider a single-hop network where nodes transmit to a base station. There are N nodes sharing the channel, and we assume that all nodes are saturated, i.e., they always have a packet to send. Node i transmits its packets following a Poisson process with a rate λ^i, which we call the channel access rate. If a packet is lost, the node retransmits the packet on its next transmission. We only consider the traffic from nodes to the base station similar to a scenario where underwater sensor nodes are reporting sensing information to the base station. We assume that the base station is not energy constrained.

We define E^i as the energy consumption per bit of the ith node and G^i as the goodput, which we define as the amount of data transmitted per unit time by node i. We assume that the packets have a fixed duration of one. We define the power required while transmission of a packet as $P_t(l, C)$ for a node with a distance l to the base station and a desired PHY-layer capacity C. To compute $P_t(l, C)$, we use the approximate model proposed in [24] based on the capacity expressions given in [2]. This model gives the optimum transmission power as a function of the capacity and distance. We also denote the power consumption between two consecutive transmissions by P_s. From now on, we refer to this intertransmission duration as *sleeping*. We assume that the transmit power control is possible as it is already present in some acoustic modems [25].

Reference [24] models the transmission power as follows:

$$P_t(l, C) = l^{a_1(C)} 10^{\frac{a_2(C)}{10}} \tag{1}$$

where

$$a_1(C) = \alpha_3 + \alpha_2 C + \alpha_1 C^2 \tag{2}$$

$$a_2(C) = \beta_3 + \beta_2 10 \log_{10} C + \beta_1 \left(10 \log_{10}(C+1)\right)^2 . \tag{3}$$

The parameters of the formula are given in Table I. Case 1 parameters are valid for $l \in [0, 10]$ km, $C \in [0, 2]$ kb/s, and Case 2 parameters are valid for $l \in [0, 100]$ km, $C \in [0, 100]$ kb/s.

In the next section, we investigate the separate optimization of PHY and MAC layers of an ALOHA-based underwater network.

IV. Separate Optimization of MAC and PHY Layers

A. MAC-Layer Optimization

Here, we first minimize the energy consumption from a MAC-layer perspective and obtain an energy-optimum channel access rate for the ALOHA network. We also compare the energy-optimum channel access rate against the channel access rate, which maximizes the MAC-layer utilization.

Since this is a single-layer analysis, we do not consider the differences among the nodes in terms of transmission power and distance. We assume that the nodes are identical in terms of PHY-layer parameters: the nodes have the same distance to the base station and have the same transmission power, i.e., $l^i = l$, $P_t(l^i, C^i) = P_t$, hence have the same PHY-layer capacity: $C^i = C$. In this case, there is no dependence on the distance, and the only parameter to optimize is the MAC-layer channel access rate, i.e., $\lambda^i = \lambda$.

Since the nodes are identical, they have the same goodput and energy consumption per bit. Hence, minimizing the energy consumption in the network is equivalent to minimizing the energy consumption of a single node.

First, we obtain the channel access rate that maximizes MAC-layer utilization. The goodput of a node can be written as

$$G(C, \lambda) = C \times U(\lambda) \tag{4}$$

where C is the PHY-layer capacity, and $U(\lambda)$ is the MAC-layer utilization, which can be written as

$$U(\lambda) = \frac{e^{-2N\lambda}}{1 + 1/\lambda} \tag{5}$$

for large N, where $1/\lambda$ is the backoff duration between transmission attempts, and $e^{-2N\lambda}$ is the probability of success of a transmission. $U(\lambda)$ is maximized at the following channel access rate:

$$\lambda^{\max} = \frac{\sqrt{N^2 + 2N} - N}{2N} \tag{6}$$

giving the following maximum utilization:

$$U^{\max} = e^{N - \sqrt{N(N+2)}} \left(N - \sqrt{N(N+2)} + 1\right). \tag{7}$$

We now aim to find the MAC-layer utilization that minimizes the energy consumption per transmitted bit. A very low utilization results in a high energy consumption per bit since the nodes spend most of their time in the sleeping state, which has a small, albeit nonnegligible, energy consumption. On the other hand, at higher channel access rates, energy will be wasted due to increased number of collisions.

The energy consumption per bit of a node can be modeled as follows: During each transmission, a node consumes a P_t amount of energy. Between each transmission, the node sleeps for a duration of $1/\lambda$; hence, the amount of energy consumed between transmissions is P_s/λ. The probability of success of a transmission is given by $e^{-2N\lambda}$, which results in the following expression for the energy consumed per bit:

$$E(C, \lambda) = \frac{P_t + P_s \frac{1}{\lambda}}{e^{-2N\lambda}} \frac{1}{C} \tag{8}$$

which is minimized at the following channel access rate:

$$\lambda^* = \frac{R}{NR + \sqrt{NR(NR+2)}} \tag{9}$$

where $R = P_s/P_t$. When (9) is replaced in (5), the following energy-optimum MAC utilization at which the energy consumption is minimized can be obtained:

$$U^* = \frac{Re^{NR - \sqrt{NR(NR+2)}}}{NR + \sqrt{NR(NR+2)} + R}. \tag{10}$$

Then, the ratio of energy-optimum utilization to the maximum utilization can be obtained by dividing (10) by (7) as follows:

$$\frac{U^*}{U^{\max}} = \frac{R \exp\left(N(R-1) - \sqrt{NR(NR+2)} + \sqrt{N(N+2)}\right)}{\left(-N + \sqrt{N(N+2)} - 1\right)\left(NR + \sqrt{NR(NR+2)} + R\right)}. \tag{11}$$

B. PHY-Layer Optimization

If the PHY-layer energy consumption is analyzed in isolation, it can be numerically shown that the required transmission power per bit is an increasing function of transmission capacity for a given l, i.e.,

$$\frac{\partial}{\partial C} \frac{P_t(l, C)}{C} > 0 \tag{12}$$

for $l > 1$ km, $C > 1$ kb/s for Case 2 and for $l > 0.008$ km for Case 1. Hence, for practical values of l and C, a node should transmit at the lowest PHY-layer transmission capacity, which satisfies the goodput constraints.

C. Separate-Layer Optimum Policies (SL-E and SL-T)

We propose two different policies that separately optimize both layers. The first policy (SL-E) sets the channel access rate of all nodes to λ^* given by (9), which minimizes MAC-layer energy consumption. Then, it selects PHY-layer transmission capacity as the minimum transmission capacity that satisfies the goodput constraint

$$G(C, \lambda^*) = \frac{Ce^{-2N\lambda^*}}{1 + 1/\lambda^*} = T \tag{13}$$

which results in the selection of the following transmission capacity:

$$C = \frac{T(1 + 1/\lambda^*)}{e^{-2N\lambda^*}}. \tag{14}$$

The second policy (SL-T) sets the channel access rate of all nodes to $\lambda^{\max}$ given by (6), which maximizes MAC-layer utilization. Similarly, the PHY-layer transmission capacity is selected as the minimum transmission capacity that satisfies the goodput constraint.

These policies are different because SL-E aims to minimize energy consumption in the MAC layer but SL-T aims to maximize MAC-layer utilization. SL-E selects a lower channel access rate and achieves a lower MAC-layer utilization in comparison with SL-T to minimize the energy wasted due to collisions. At first glance, it can be thought that SL-E consistently consumes less energy than SL-T since it minimizes MAC-layer energy consumption. When both layers are taken into consideration, however, SL-E consumes more energy than SL-T if the nodes have high goodput requirements. Since SL-E achieves a lower MAC utilization, a higher transmission power should be used to compensate if the desired goodput is high. This results in significant energy consumption due to PHY layer despite the energy-optimum MAC layer. More detailed comparison between these policies is given in Section VI.

V. Cross-Layer Optimization of MAC and PHY Layers

Here, we investigate how the probing rates and transmission powers of nodes are jointly optimized in an ALOHA network so that the energy consumption of the network is minimized.

In contrast to the MAC-layer analysis in the previous section, we now consider the differences in distance l and transmission capacity C, among the nodes. For the ith node, the energy consumption during packet transmission is $P_t(l^i, C^i)$, and the average energy consumption between consecutive transmissions is $P_s \times 1/\lambda^i$, where λ^i is the channel access rate of the node. The amount of data transmitted during a packet transmission is C^i. If we denote the probability of success of the transmission as $\text{Prob}^i_{\text{succ}}$, then successful transmission of a packet requires $1/\text{Prob}^i_{\text{succ}}$ transmissions on the average. Thus, the energy consumption per bit of a node can be written as follows:

$$E^i(C^i,\lambda^i) = \frac{P_t(l^i,C^i)+P_s\frac{1}{\lambda^i}}{\text{Prob}^i_{\text{succ}}}\frac{1}{C^i} = \frac{P_t(l^i,C^i)+P_s\frac{1}{\lambda^i}}{e^{-2\sum_{j:j\neq i}\lambda^j}}\frac{1}{C^i} \tag{15}$$

since the probability success of a transmission can be written as $\text{Prob}^i_{\text{succ}} = e^{-2\sum_{j:j\neq i}\lambda^j}$ for an ALOHA network. Similarly, the average goodput of a node can be written as

$$G^i(C^i,\lambda^i) = \frac{C^i \text{Prob}^i_{\text{succ}}}{1+1/\lambda^i} = \frac{C^i e^{-2\sum_{j:j\neq i}\lambda^j}}{1+1/\lambda^i}. \tag{16}$$

Using these metrics, we can define the cross-layer energy-optimum policy as follows.

Cross-Layer Energy Optimum Policy (CL): The energy minimization problem can be formulated as follows:

$$\begin{aligned} \min \quad & \frac{\sum_i E^i(C^i,\lambda^i)G^i(C^i,\lambda^i)}{\sum_i G^i(C^i,\lambda^i)} \\ \text{subject to} \quad & G^i(C^i,\lambda^i) = T^i \\ & 0 < C^i < \overline{C} \\ & 0 < \lambda^i \end{aligned} \tag{17}$$

where the decision variables are λ^i and C^i. C^i is upper bounded by $\overline{C}$, which is the maximum transmission capacity, which is supported by the approximate model. For Case 1, $\overline{C} = 2$, and for case 2, $\overline{C} = 100$. If the goodput constraints of all nodes are equal, i.e., $T^i = T$, the problem can be reduced as follows due to the equality constraint:

$$\begin{aligned} \min \quad & \sum_i E^i(C^i,\lambda^i) \\ \text{subject to} \quad & G^i(C^i,\lambda^i) = T \\ & 0 < C^i < \overline{C} \\ & 0 < \lambda^i. \end{aligned} \tag{18}$$

Due to the nonlinear equality constraint, this optimization problem is not convex. We solve this optimization problem using sequential quadratic programming [26] through MATLAB Optimization Toolbox. Solution for an 11-node network is quite fast, which takes a few seconds on a typical laptop computer.

VI. Numerical Results

In this part, we evaluate the performance of the cross-layer optimization in comparison with separate optimization of both layers. We first evaluate the policies for a large-scale network with 11 nodes with distances [1, 10:10:100] km to the base station. Then, we evaluate the policies for a small-scale network where the nodes have [0.1, 1:1:10] km distance to the base station. In these evaluations, we used the approximate model given in [24]: For the large-scale network, we use the model defined as *Case 2*, which is valid for $l \in [0, 100]$ km and $C \in [0, 100]$ kb/s, and for the small-scale network, we use the model defined as *Case 1*, which is valid for $l \in [0, 10]$ km and $C \in [0, 2]$ kb/s.

The operation of the pure ALOHA protocol is not affected by the distance or exact location of the nodes since the nodes do not perform carrier sensing. We assumed that the power consumed while sleeping is 1/300 of the transmit power over a medium range at a medium rate, i.e., $P_s = P_t(50, 50)/300$ for the large-scale network and $P_s = P_t(5, 1)/300$ for the small-scale network, since the sleeping power of the WHOI micromodem is approximately 1/300 of its transmit power [27]. We assume a packet transmission duration of 1 s. We omit the energy consumption during the wake-up of the nodes.

We also performed simulations to evaluate the accuracy of the results obtained using the considered policies. We have implemented an ALOHA simulator using Java. In these simulations, we have assumed that the packets can be transmitted at the full capacity.

A. Large-Scale Network

Figs. 1 and 2 plot the change in the capacity and channel access rate allocations of CL, SL-E, and SL-T policies for the 11 nodes in the network with respect to their distance. SL-E and SL-T policies first select a channel access rate that optimizes MAC-layer energy consumption and MAC-layer utilization, respectively. This selection is independent from the distance of

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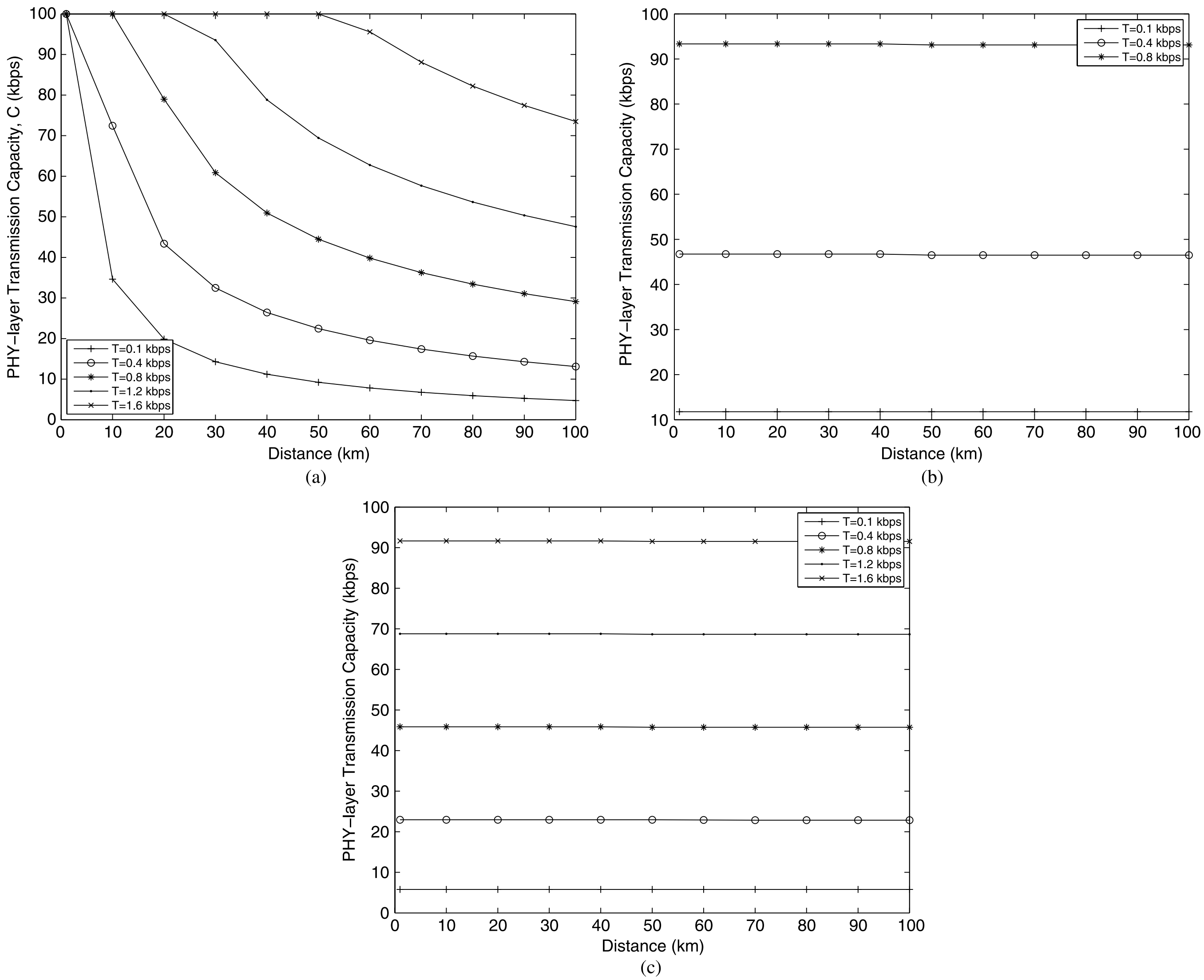
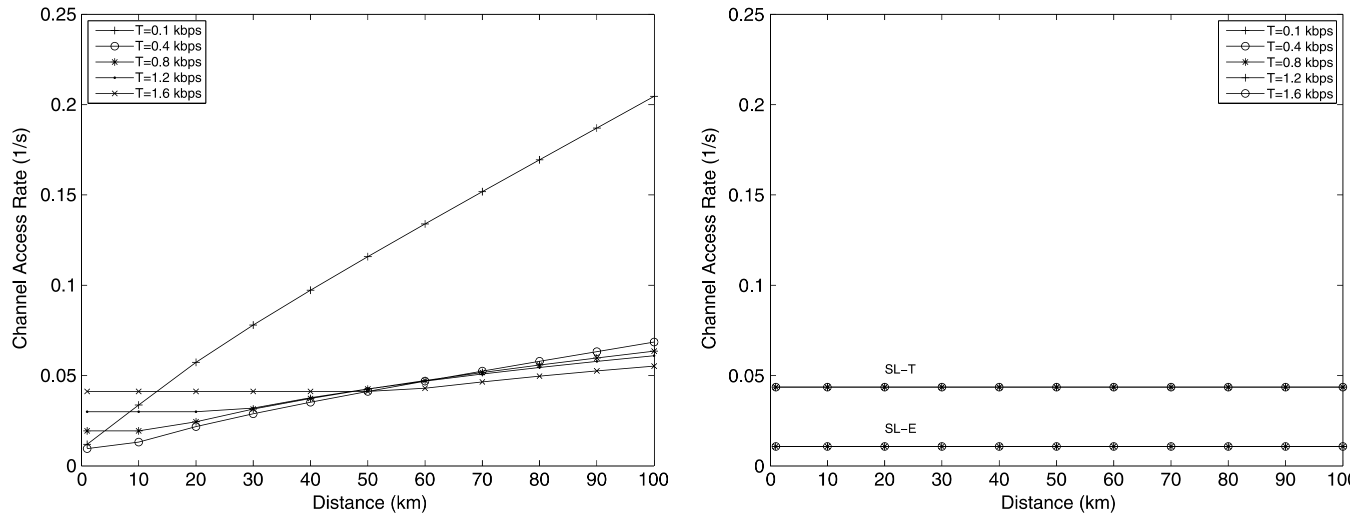


Fig. 1. Capacity allocations made by the (a) proposed cross-layer policy (CL) and (b) SL-E and (c) SL-T for nodes with increasing distance to the base station for different goodput requirements. (Large-scale network).

the node, as shown in Fig. 2(b), since SL policies optimize each layer in isolation. SL-E selects a lower access rate than SL-T since the access rate that minimizes energy consumption given by (9) is lower than the access rate that maximizes utilization given by (6). SL-E and SL-T then select the minimum PHY-layer transmission capacity to satisfy the goodput requirement of each node, as shown in Fig. 1(b) and (c). Since SL-E selects a low MAC-layer access rate, it cannot satisfy higher goodput requirements within the limits of the PHY-layer transmission capacity (100 kb/s), as presented in Fig. 1(b). This is one of the disadvantages of separate optimization of network layers: Isolated optimization of the MAC-layer energy consumption results in a low channel utilization, which may prevent the goodput requirements to be satisfied for a large-scale network.

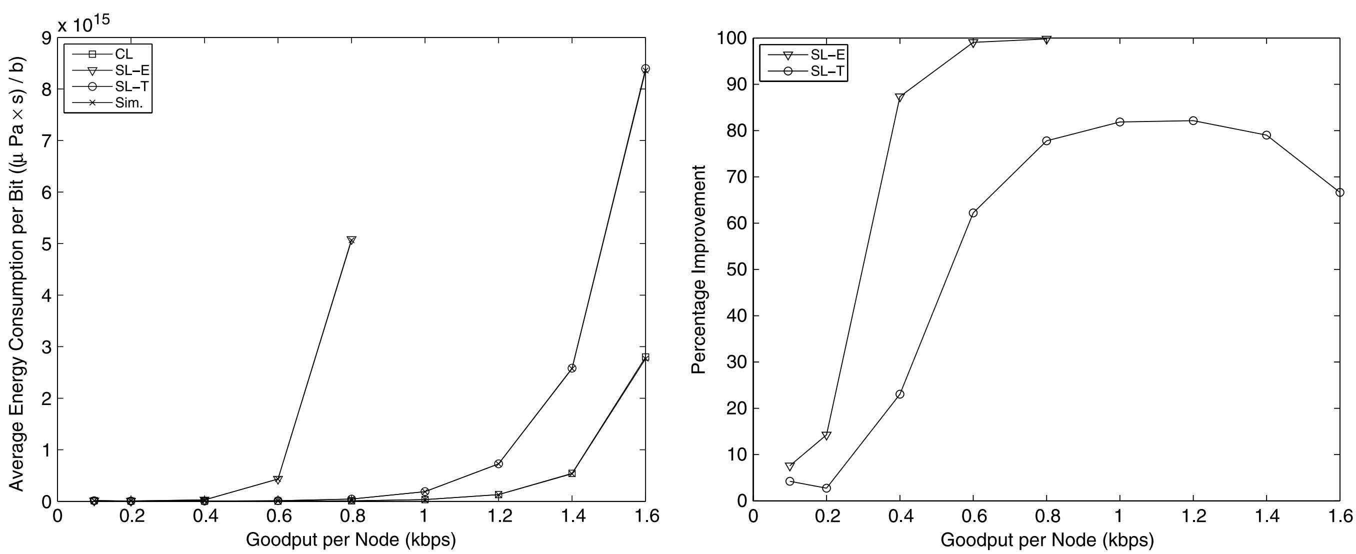
In contrast to SL-E and SL-T, which assign a fixed channel access rate and transmission capacity regardless of distance, CL selects these parameters depending on the distance of a node. CL allocates a higher PHY-layer transmission capacity to the nodes that have a shorter distance to the base station, i.e., which have a better channel [see Fig. 1(a)]. To compensate for the disadvantage of nodes that are farther away from the base station, CL assigns higher channel access rates to distant nodes [see Fig. 2(a)]. In other words, CL assigns higher PHY-layer resources to the closer nodes and higher MAC-layer resources to more distant nodes, equalizing the goodput among the nodes.

The benefit of this joint optimization is apparent in the energy consumption per successfully transmitted bit. Fig. 3(a) presents the energy consumed per bit as the goodput of nodes increases, and Fig. 3(b) presents the percentage improvement obtained by CL in terms of energy consumption per bit. Fig. 3(a) also plots the simulation results, which predict the energy consumption very accurately. Among the studied policies, CL consumes the lowest amount of energy per bit due to cross-layer optimization. The improvement obtained by CL in the energy consumption can reach 66% in comparison with SL-T. The energy consumption of SL-E can reach extremely high values at higher goodputs resulting up to 100 times more energy consumption than CL.



(a) (b)

Fig. 2. Channel access rate allocations made by (a) CL and (b) SL-E and SL-T for nodes with increasing distance to the base station for different goodput requirements. (Large-scale network).



(a) (b)

Fig. 3. (a) Average energy consumption per bit for CL and SL policies as the goodput per node increases. (b) Percentage improvement obtained by CL. (Large-scale network).

SL-T consumes less energy than SL-E, which demonstrates an interesting aspect of single-layer optimization: Although SL-E optimizes the MAC-layer energy consumption by selecting a low channel access rate, it requires a high PHY-layer transmission capacity if there is a high goodput requirement. This increase in the PHY-layer transmission capacity causes a significant energy consumption, which exceeds the energy savings obtained from MAC-layer optimization.

B. Small-Scale Network

We also evaluate the proposed cross-layer policy for a small-scale network that has a radius of 10 km. For this network, we use the approximate model given in [24] as Case 1. Figs. 4 and 5 show the transmission capacity and channel access rate allocations made by the evaluated policies. SL-E selects a lower access rate than SL-T, similar to the large-scale network (see Fig. 5). As a result, SL-E assigns higher transmission capacity to nodes in comparison with SL-T [see Fig. 4(c) and (b)]. CL assigns higher transmission rates to the closer nodes and assigns higher channel access rates to the distant nodes similar to the previous case.

Although the behavior of CL is similar for the small-scale network and the large-scale network, there is a subtle difference between the access rate and transmission capacity allocations. For the large-scale network, CL tends to select channel access rates closer to SL-T on the average and higher in comparison with SL-E (see Fig. 2). On the other hand, for the small-scale network, CL assigns lower channel access rates in comparison

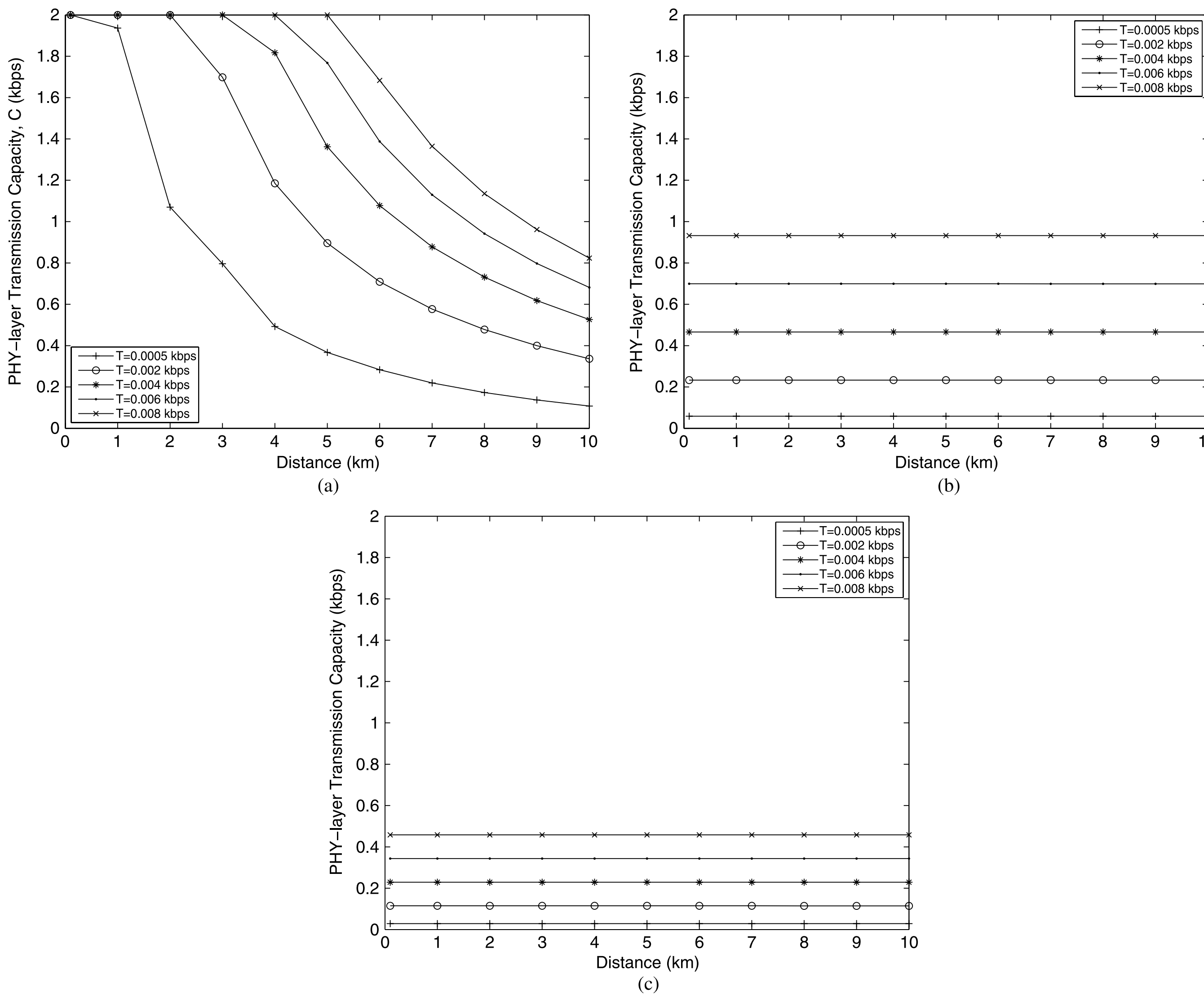


Fig. 4. Capacity allocations made by the (a) proposed cross-layer policy (CL) and (b) SL-E and (c) SL-T for nodes with increasing distance to the base station for different goodput requirements. (Small-scale network).

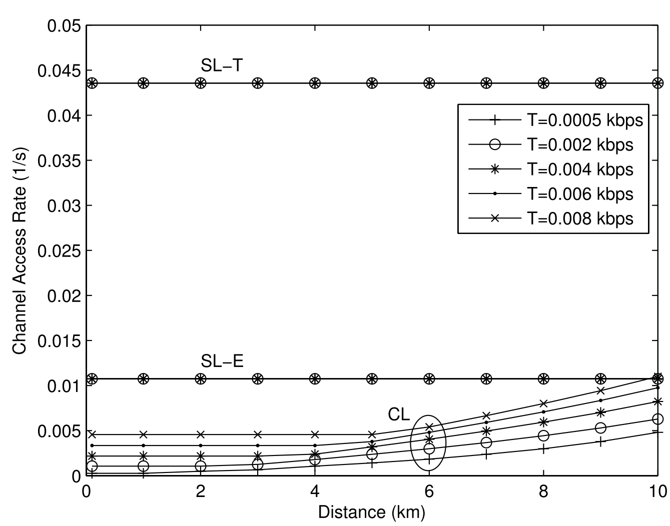


Fig. 5. Channel access rate allocations made by CL and SL-E and SL-T for nodes with increasing distance to the base station for different goodput requirements. (Small-scale network).

with both SL-T and SL-E (see Fig. 5). The reason is the following: For a large-scale network, the PHY layer is very inefficient due to long transmission distance. For that reason, CL aims to minimize the PHY-layer transmission capacity and increase the channel access rates such that the MAC-layer utilization is maximized. Hence, for the large-scale network, the channel access rates assigned by CL is closer to SL-T on the average. On the other hand, PHY layer of the small-scale network is more efficient in comparison with a large-scale network. Hence, for the small-scale network, CL assigns lower channel access rates in the MAC layer to minimize collisions and maximize PHY-layer transmission capacity.

The energy consumption of all policies and the amount of improvement obtained by CL are shown in the results in Fig. 6. In comparison with the large-scale network, the improvement obtained by cross-layer optimization is less significant. The improvement reaches up to 7 in comparison with SL-E and 44 in comparison with SL-T. Large-scale network has a higher improvement margin because it has a very inefficient PHY layer, and a poor choice of channel access rates require

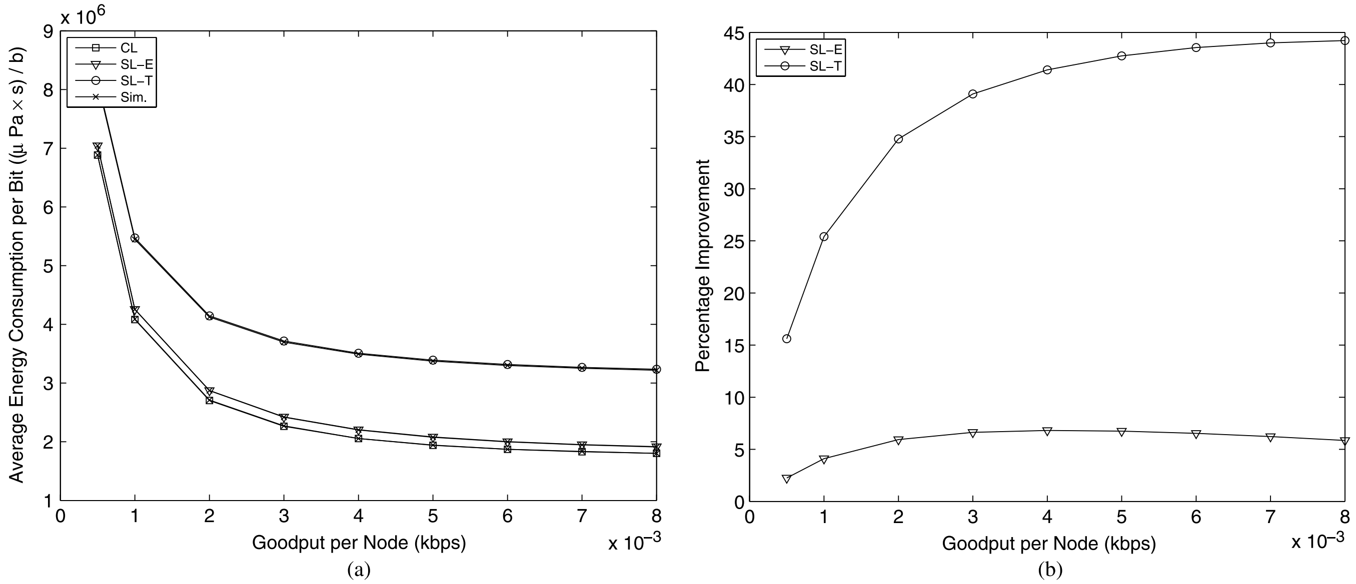


Fig. 6. (a) Average energy consumption per bit for CL and SL policies as the goodput per node increases. (b) Percentage improvement obtained by CL. (Small-scale network).

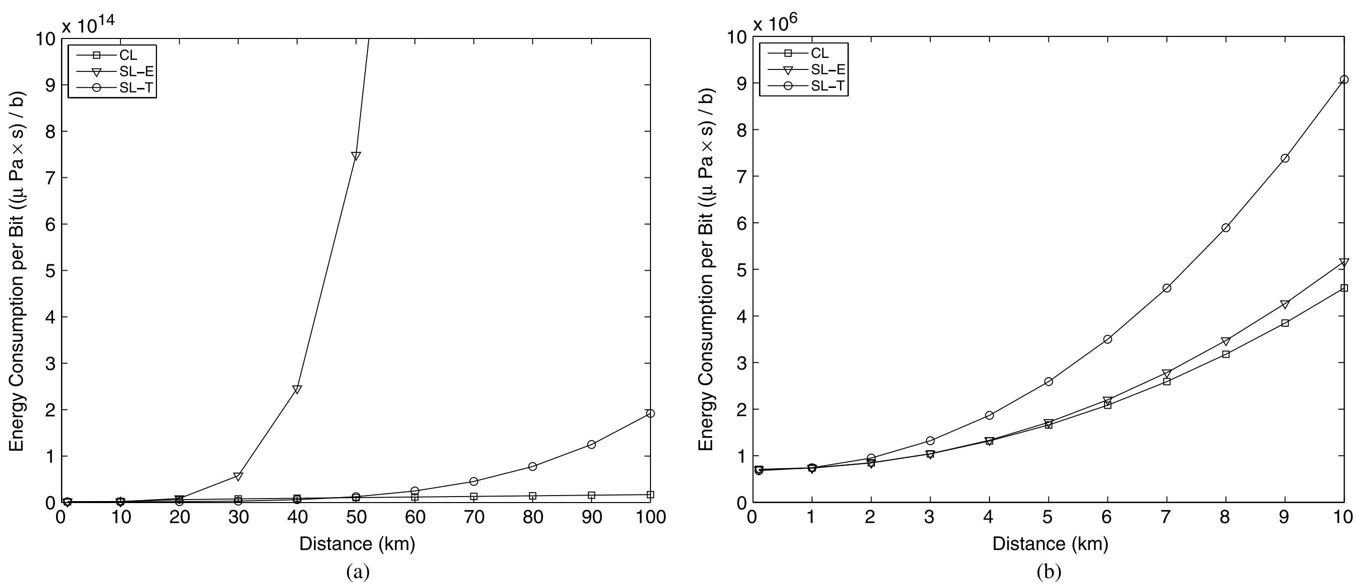


Fig. 7. (a) Energy consumption per bit for each node for $T = 0.8$ for the large-scale network. (b) Energy consumption per bit for each node for $T = 0.004$ for the small-scale network.

nodes to use higher transmission powers. Hence, cross-layer optimization minimizes the effect of inefficient PHY layer by giving MAC-layer priority to distant nodes.

It should be also noted that the best separate-layer policy is different for the small-scale and large-scale networks. For the large-scale network, SL-T is more efficient than SL-E, and for the small-scale network, SL-E is more efficient than SL-T. SL-T is more efficient for the large-scale network as MAC-layer utilization should be as high as possible to use the minimum transmission power. On the other hand, SL-E is more efficient for the small-scale network since it has a more efficient PHY layer, which makes the energy wasted due to collisions more dominant. Since there is no single best separate-layer policy, cross-layer optimization is crucial for energy efficiency.

C. Node Failure Time Analysis

In this part, we investigate the effect of cross-layer optimization on the lifetime of nodes in an underwater sensor network. Fig. 7(a) plots energy consumption per bit for each node at $T = 0.8$ for a large-scale network, and Fig. 7(b) plots the energy consumption per bit for each node at $T = 0.004$ for a small-scale network. The energy consumption among the nodes is more homogeneous for the CL policy in comparison with SL-E and SL-T, particularly for the large-scale network. For the SL

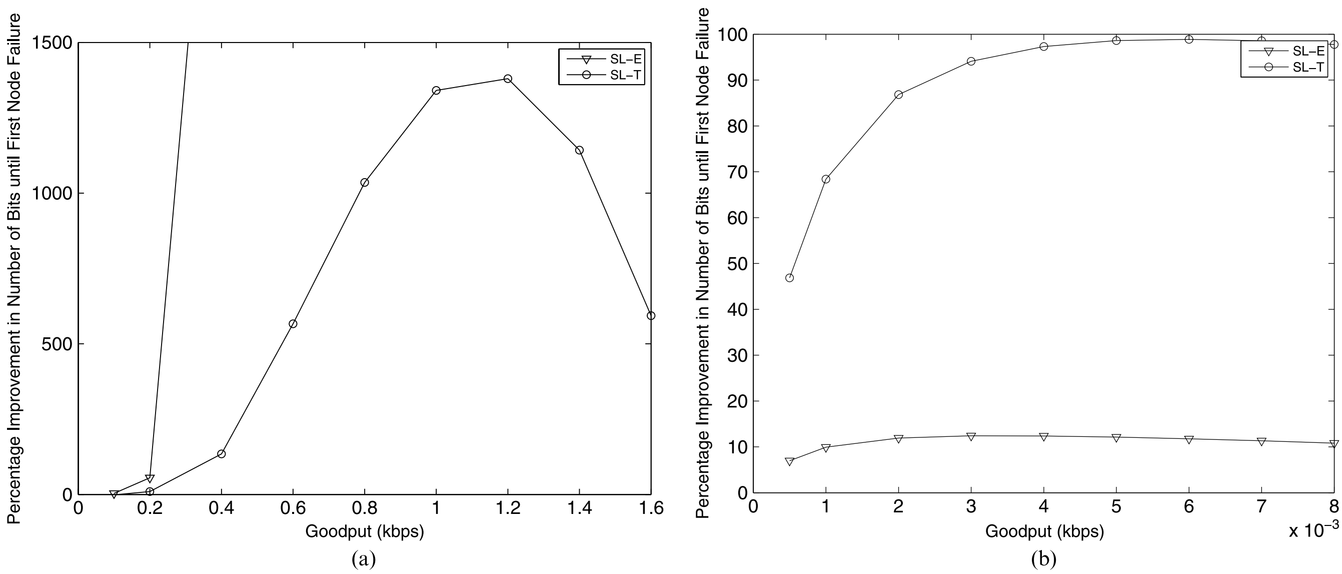


Fig. 8. Improvement with CL compared with SL-E and SL-T in the number of bits transmitted during the network's lifetime as a function of node goodput for the (a) large-scale network and for the (b) small-scale network.

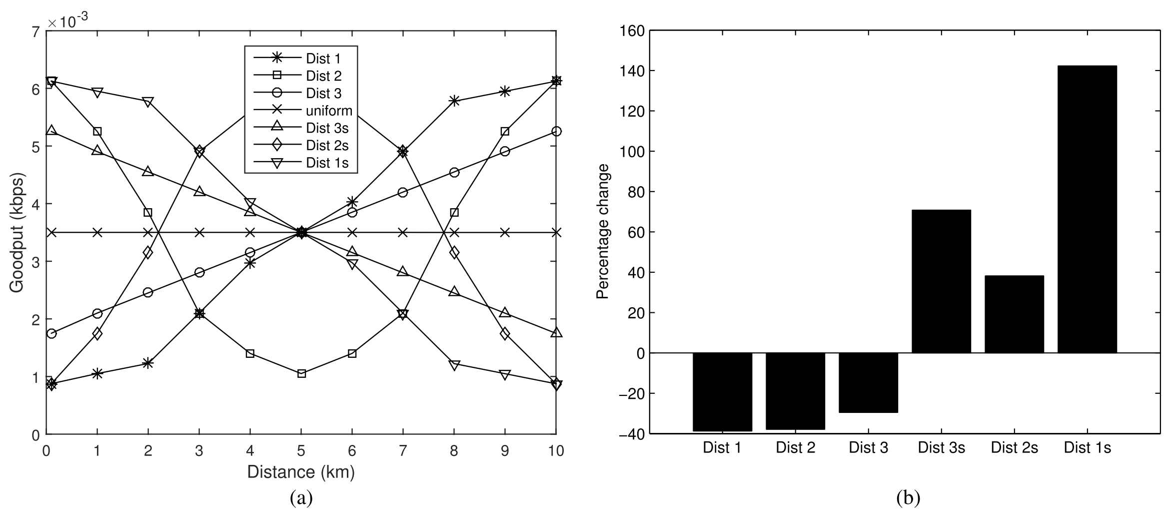


Fig. 9. (a) Goodput distribution of nodes that we have evaluated. (b) Percentage change in the number of bits until first node failure in comparison with the uniform goodput distribution.

policies, the nodes that are far from the base station are required to transmit at very high power levels, which will degrade their lifetime if they have a limited energy supply such as battery.

The improvement obtained by CL in the number of bits transferred until the first node failure is shown in Fig. 8. For a large-scale network, CL improves the lifetime up to 14 times in comparison with SL-T. SL-E performs very poor due to the increased transmission power as previously discussed. For the small-scale network, the improvement is up to 13% in comparison with SL-E and up to 98% in comparison with SL-T. Cross-layer optimization also prolongs the lifetime of the network in addition to improving the overall energy consumption. This aspect of cross-layer optimization may become very crucial in settings where the recharging of battery-powered underwater nodes is difficult.

D. Nonuniform Traffic Load

So far, we have investigated the case where the nodes have equal goodput constraints to perform a fair comparison between nodes. In practice, however, different goodput requirements among the nodes may exacerbate the asymmetry in the energy consumption. This asymmetry may affect the lifetime of the network, as the nodes with greater goodput requirements may run out of power earlier than the lightly loaded nodes. To study this possible situation, we have evaluated different goodput distributions using the CL policy. We consider the goodput distributions shown in Fig. 9(a), which are selected such that the total goodput requirements for all distributions are equal to the uniform distribution case.

Our results show that such an asymmetry may shorten the lifetime of the network for some distributions, but it may also prolong it. The time until the first node failure is determined by the node with the worst channel condition when the goodput requirements are equal. If the goodput requirements of the weakest node are less than the other nodes, such an asymmetry may prolong the time until the first node failure. For example, Fig. 9(b) shows the change in the time until the first node failure in comparison with the uniform goodput distribution. If the goodput distribution is skewed toward the nodes with good channel conditions (i.e., closer to the base station), the lifetime improves. For example, for *Dist 1s*, closer nodes have greater throughput requirements, which prolongs the lifetime of the network by 140% in comparison with a uniform goodput distribution. On the other hand, its symmetric version *Dist 1* reduces the lifetime of the network by 40%.

VII. Conclusion

We have analyzed the energy consumption of an underwater ALOHA network both from a layered perspective and from a cross-layer perspective. We show that compensating the PHY-layer disadvantage of distant nodes by increasing their MAC-layer utilization results in a significantly more energy efficient underwater network. The improvement obtained by cross-layer optimization reaches up to 66% for a large-scale network in comparison with the separate optimization of PHY and MAC layers. Our results also show that cross-layer optimization is more crucial for large-scale networks where the required transmission powers are much higher. A MAC-layer-only optimization, which does not consider the PHY layer, may cause higher energy consumption in the PHY layer, exceeding the benefits of the MAC-layer optimization.

In addition to an overall energy consumption improvement, the individual energy consumption of nodes is more homogeneously distributed by a cross-layer policy, which prolongs the time until the first node failure. As a result, the amount data transmitted until the first node failure can be increased significantly by a cross-layer policy.

In this paper, we have considered a single-hop scenario where the nodes do not perform multihopping to reduce transmission power. Although multihopping has been used to reduce transmission power, nodes have to stay in the receive state to perform relaying functions [28]. Hence, the nodes cannot switch to a low-power sleep phase to reduce energy consumption. In a sensor networking scenario similar to what we consider, the nodes transmit data on the uplink and close their transmission circuits immediately to conserve power. For that reason, we do not expect that multihopping will improve the energy consumption for the scenario considered here, but the tradeoff between multihopping and single hopping should be investigated for different underwater communication scenarios as a future study.

References

[1] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "Aloha-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proc. IEEE INFOCOM*, May 2007, pp. 2271–2275.

[2] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 11, no. 4, pp. 34–43, Oct. 2007.

[3] N. Abramson, "THE ALOHA SYSTEM: Another alternative for computer communications," in *Proc. AFIPS*, 1970, pp. 281–285.

[4] A. A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *Proc. 2nd ACM Int. WUWNet*, Sep. 2007, pp. 41–48.

[5] L. Pu *et al.*, "Comparing underwater MAC protocols in real sea experiments," *Comput. Commun.*, vol. 56, pp. 47–59, Feb. 2015.

[6] L. Vieira, J. Kong, U. Lee, and M. Gerla, "Analysis of ALOHA protocols for underwater acoustic sensor networks," in *Proc. 1st ACM Int. WUWNet*, Los Angeles, CA, USA, Sep. 2006.

[7] J. Ahn, A. Syed, B. Krishnamachari, and J. Heidemann, "Design and analysis of a propagation delay tolerant ALOHA protocol for underwater networks," *Ad Hoc Netw.*, vol. 9, no. 5, pp. 752–766, Jul. 2011.

[8] S. De, P. Mandal, and S. S. Chakraborty, "On the characterization of Aloha in underwater wireless networks," *Math. Comput. Model.*, vol. 53, no. 11/12, pp. 2093–2107, Jun. 2011.

[9] P. Mandal, S. De, and S. S. Chakraborty, "A receiver synchronized slotted Aloha for underwater wireless networks with imprecise propagation delay information," *Ad Hoc Netw.*, vol. 11, no. 4,pp. 1443–1455, Jun. 2013.

[10] H. Baek, J. Lim, and S. Oh, "Beacon-based slotted ALOHA for wireless networks with large propagation delay," *IEEE Commun. Lett.*, vol. 17, no. 11, pp. 2196–2199, Nov. 2013.

[11] L. Pu *et al.*, "Impact of real modem characteristics on practical underwater MAC design," in *Proc. OCEANS—Yeosu*, May 2012, pp. 1–6.

[12] Y. Zhu *et al.*, "Toward practical MAC design for underwater acoustic networks," in *Proc. IEEE INFOCOM*, 2013, pp. 683–691.

[13] Z. Zhou, Z. Peng, P. Xie, J.-H. Cui, and Z. Jiang, "Exploring random access and handshaking techniques in underwater wireless acoustic networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2013, no. 1, p. 95, Apr. 2013.

[14] Y. Xiao, Y. Zhang, J. Gibson, G. Xie, and H. Chen, "Performance analysis of ALOHA and p-persistent ALOHA for multi-hop underwater acoustic sensor networks," *Cluster Comput.*, vol. 14, no. 1, pp. 65–80, Mar. 2011.

[15] H. Yu, N. Yao, S. Cai, and Q. Han, "Analyzing the performance of Aloha in string multi-hop underwater acoustic sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2013, no. 1, p. 65, Mar. 2013.

[16] M. K. Park and V. Rodoplu, "UWAN-MAC: An energy-efficient MAC protocol for underwater acoustic wireless sensor networks," *IEEE J. Ocean. Eng.*, vol. 32, no. 3, pp. 710–720, Jul. 2007.

[17] P. Xie and J.-H. Cui, "R-MAC: An energy-efficient MAC protocol for underwater sensor networks," in *Proc. Int. Conf. Wireless Algorithms, Syst. Appl.*, Aug. 2007, pp. 187–198.

[18] D. Pompili, T. Melodia, and I. Akyildiz, "A CDMA-based medium access control for underwater acoustic sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1899–1909, Apr. 2009.

[19] A. Syed, W. Ye, and J. Heidemann, "T-Lohi: A new class of MAC protocols for underwater acoustic sensor networks," in *Proc. IEEE INFOCOM*, Apr. 2008, pp. 231–235.

[20] F. Fazel, M. Fazel, and M. Stojanovic, "Random access compressed sensing for energy-efficient underwater sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1660–1670, Sep. 2011.

[21] C. Kam, S. Kompella, G. Nguyen, A. Ephremides, and Z. Jiang, "Frequency selection and relay placement for energy efficiency in underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 39, no. 2, pp. 331–342, Apr. 2014.

[22] J. Jornet, M. Stojanovic, and M. Zorzi, "On joint frequency and power allocation in a cross-layer protocol for underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 35, no. 4, pp. 936–947, Oct. 2010.

[23] M. Zorzi, P. Casari, N. Baldo, and A. Harris, "Energy-efficient routing schemes for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1754–1766, Dec. 2008.

[24] D. Lucani, M. Medard, and M. Stojanovic, "Underwater acoustic networks: Channel models and network coding based lower bound to transmission power for multicast," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1708–1719, Dec. 2008.

[25] E. Gallimore *et al.*, "The WHOI micromodem-2: A scalable system for acoustic communications and networking," in *Proc. OCEANS*, Sep. 2010, pp. 1–7.

[26] P. T. Boggs and J. W. Tolle, "Sequential quadratic programming," *Acta Numer.*, vol. 4, pp. 1–51, 1995.

[27] WHOI Micro-Modem Overview, Accessed: 2014 06 30. [Online]. Available: http://acomms.whoi.edu/micro-modem/

[28] M. Haenggi and D. Puccinelli, "Routing in ad hoc networks: A case for long hops," *IEEE Commun. Mag.*, vol. 43, no. 10, pp. 93–101, Oct. 2005.

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