Trade-off Analysis of Underwater Acoustic Sensor Networks

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Abstract. In the last couple of decades, Underwater Acoustic Sensor Networks (UASNs) were started to be used for various commercial and non-commercial purposes. However, in underwater environments, there are some specific inherent constraints, such as high bit error rate, variable and large propagation delay, limited bandwidth capacity, and short-range communications, which severely degrade the performance of UASNs and limit the lifetime of underwater sensor nodes as well. Therefore, proving reliability of UASN applications poses a challenge. In this study, we try to balance energy consumption of underwater acoustic sensor networks and minimize end-to-end delay using an efficient node placement strategy. Our simulation results reveal that if the number of hops is reduced, energy consumption can be reduced. However, this increases end-to-end delay. Hence, application-specific requirements must be taken into consideration when determining a strategy for node deployment.

1. Introduction

Underwater Acoustic Sensor Networks (UASNs) are used for various purposes in a variety of underwater applications, such as underwater data collection, coastal surveillance, oil monitoring, pollution detection, and seismic and volcanic prediction [1]. UASNs typically consist of two types of entities: nodes and a surface gateway to communicate to the external world. In UASNs, to measure different parameters such as conductivity, oxygen, pH, salinity, temperature, turbidity, and depth, sensors and probes are installed in the nodes and the nodes are deployed at the monitoring site. While, in Underwater Wireless Sensor Networks, the transmission of information between the sensor nodes can be realized in the form of acoustic, electromagnetic, or optical waves, acoustic communication is the communication solution in UASN applications [2].

Because of the nature of aquatic environments, there exist a variety of constraints, most importantly high propagation delay, high bit error rate (BER), low/medium bandwidth, and short-range communications [3]. These constraints both degrade the performance of UASNs and limit the lifetime of underwater sensor nodes, and hence call for the deployment of many underwater sensor nodes for successful UASNs. Although UASNs can be deployed using different approaches, it is a significant challenge because of the abovementioned constraints. In addition, approximate cost of underwater sensor nodes is much more than terrestrial wireless sensor nodes and this limits the number nodes to be deployed and eliminates some deployment approaches.

For the performance and success of UANs, deployment strategies play a key role since they need to address the major goals such as ensuring full-connectivity coverage and optimizing network lifetime. In addition, the deployment strategies must take into consideration major network and/or node-related factors including packet reception rate, delay, throughput, transceiver power, battery density, and CPU
power [4]. Since UASN nodes are powered by internal/external batteries, they should be properly placed to minimize path loss and energy consumption. Typically, UASN nodes maintain their locations using their location and depth adjustment capabilities. Different types of manned or unmanned vehicles including boats, submarines, and aerial vehicles can be used for the initial deployment.

In this study we focus on analyzing the relations between energy consumption and number of hops and between end-to-end delay and number of hops for UASNs. The rest of the paper is structured as follows. The theory and results of a set of simulation studies carried out to analyze the effects of node placement on energy consumption and end-to-end delay are presented in Section II. Section III concludes the paper.

2. Effects of Node Placement on Energy Consumption and End-To-End Delay

In this section we present the details of a case study based on an orthogonal dam model and a simulation study to find out the effects of node placement on network energy consumption and end-to-end delay for the UASN. For the UASN, a sufficient number of underwater sensor nodes must be deployed to cover the volume of the dam model. Since the underwater sensor nodes communicate with each other using acoustic links, the path loss is caused by the energy spreading and the wave absorption [5]. In UASNs, mainly, while the former is dependent on transmission range [6, 7], the latter is frequency-dependent.

In the case study, two-dimensional (2D) acoustic communications were considered. Therefore, we assume that UASN nodes are equipped with the same model transceiver and cylindrical-based communication capability with a constant radius of $d$. Under this assumption, two underwater sensor nodes can communicate if the distance between the nodes is $\leq d_{\text{max}}$. Moreover, all the nodes transmit with the same transmission power. In addition, all of the environmental parameters apply to all the nodes.

Let the UASN node $n_i$ be located at a distance of $d$ from the gateway and send its data packets to the gateway over a multiple-hop path $h_1h_2...h_N$ [8]. For the node $n_i$, the source signal level $SSL$ which depends on the transmission power $TP$ of the transceivers can be expressed by equation (1) [5, 7, 9].

$$SSL = ANL + SNR + TL - DI$$

where $ANL$ represents the ambient noise level, $SNR$ represents the signal-to-noise ratio at the transceiver, $TL$ represents the transmission loss, and $DI$ represents the directivity index. $ANL$ increases in shallow water and depends on frequency and many other factors such as waves, wind, and surface-level activities. In the case study, $ANL$ was assumed to be 50 dB based on the measurements in the literature [6]. Under the assumption of omnidirectional hydrophones, $DI$ is assumed to be zero. Therefore, $SSL$ can be expressed as a function of $TL$ and $SNR$ (2) and $TL$ can be approximated as using equation (3) [6, 8]. $SSL$ can also be expressed as the transmitted signal intensity at depth of 1 m using equation (4).

$$SSL = TL + SNR + 50$$

$$TL = 10\log d + ACd \times 10^{-3} + TA$$

where $d$ represents the distance between the sender and receiver in meters, $AC$ represents the absorption coefficient, and $TA$ represents the transmission anomaly.

$$SSL = 10\log \frac{SIT}{\mu Pa}$$

where $SIT$ represents the intensity of underwater signal in $\mu Pa$ and can be expressed using equation (5). To achieve the intensity $SIT$ at a distance of 1 m from the sender to the receiver, the
transmission power $TP$ needed can be expressed using equation (6) [6, 8].

$$\text{SIT} = 10^{\text{SSL}/10} \times 0.67 \times 10^{-18}$$

$$TP = 2\pi \times 1m \times h \times \text{SIT}$$

(5) (6)

where $h$ represents the water depth in m.

In the case study, Orthogonal Frequency Division Multiplexing (OFDM) encoding and 16-Quadrature Amplitude Modulation (QAM) was assumed [10, 11]. In the UASN, the end-to-end delay $EED$ can be expressed using equation (7) [8, 11].

$$EED = N(t_{\text{prop}}(i,i+1) + t_{\text{pkt}})$$

(7)

where $t_{\text{prop}}(i,i+1)$ is the propagation time between underwater sensor nodes $i$ and $i + 1$, $t_{\text{pkt}}$ is the time required to transmit a data packet, and $N$ is the number of hops. The time required to transmit a data packet can be expressed using equation (8) and the propagation time can be expressed using equation (9).

$$t_{\text{pkt}} = \frac{PL}{DR}$$

(8)

$$t_{\text{prop}} = \frac{d}{PV}$$

(9)

where $PL$ represents packet length, $DR$ represents data rate, and $PV$ represents the propagation velocity of the acoustic waves in water.

In the case study, the effects of placing two or more intermediate hops on the energy consumption and the end-to-end delay of the UASN were investigated. Based on the parameters [12, 13] listed in Table 1, a set of simulation studies was realized. Figure 1, Figure 2, and Figure 3 show energy consumption while sending one data packet. In the case study, distances between nodes of 125 m, 250 m, and 500 m were considered. The results indicate that when the number of hops is increased, the energy consumption decreases. Figure 4 shows the end-to-end delay as a function of the number of hops for distances between nodes of 125 m, 250 m, and 500 m. It can be seen that the end-to-end delay increases when the number of hops is increased. The results reveal that the number of hops should be correctly determined because there is a significant trade-off between UASN energy consumption and end-to-end delay.

**Table 1. Simulation parameters**

| Parameter                     | Value                        |
|-------------------------------|------------------------------|
| Temperature                   | 15°C                         |
| Frequency                     | 40 KHz                       |
| Absorption Coefficient        | 8.96 dB/km                   |
| Maximum Depth (Height)        | 100 m                        |
| Transmission Anomaly          | 5 dB                         |
| Propagation Velocity          | 1466 m/s at 15°C [13]        |
| Packet Length                 | 512 bits                     |
| Data Rate                     | 1 Kbps                       |
| Noise Bandwidth               | 1 kHz                        |
| BER                           | $10^{-9}$                     |
Figure 1. Energy consumption while sending one data packet at depth of 100 m. Transmission power with different hops at depth of 100 m and distance of 125 m.

Figure 2. Energy consumption while sending one data packet at depth of 100 m. Transmission power with different hops at depth of 100 m and distance of 250 m.

Figure 3. Energy consumption while sending one data packet at depth of 100 m. Transmission power with different hops at depth of 100 m and distance of 500 m.
3. Conclusion
Although there is an increasing interest in UASNs due to their unique capabilities, the efficiency of UASNs and the lifetime of sensor nodes are greatly affected by a number of constraints including short-range communications, long propagation latency, limited bandwidth capacity, and variable bit error rate. To address these issues efficiently, the use of field experiments and test beds is essential and supports more accurate performance analysis and system characterization. Such work can increase overall robustness in different conditions and enable the analysis of total system cost and energy requirements. On the other hand, investigating and handling these issues are difficult due to the high cost and complexity of trials and field experiments, emulation and hardware-in-the-loop technologies, and physics-based simulation which should be used to estimate performance and must be designed to involve the presence of shadow zones, jamming, and natural interference. Due to the unavailability of such environments, in this paper, with a set of performance evaluations, the trade-offs between end-to-end delay, UASN energy consumption and number of hops was investigated to find out the optimal number of hops which satisfies both end-to-end delay and overall network energy consumption requirements. Our simulation results revealed that increasing the number of hops between the sender and receiver reduces energy consumption significantly but increases end-to-end delay.

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