Network Computing for Distributed Underwater Acoustic Sensors

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Table of contents

List of figures

List of tables

1 Introduction

We conduct research on Underwater Acoustic Sensor Networks (UASNs). The two main research themes are reviewed in Sections 2 and 3. Section 2 outlines a methodology for physical layer simulation, with upper layer protocol integration. Section 3 describes new ideas for location-free routing. Details of the work can be found in the forthcoming publications [1] and [2]. Section 4 describes conclusions and future work.

2 Physical layer in UASNs

Our main investigations are about underwater communications using acoustic waves. Electromagnetic and optical waves do not work well underwater due to the nature of the medium, especially in the case of seawater. Acoustic waves are used for underwater communication due to the relatively low attenuation (i.e., signal reduction) of sound in water, specially in thermally stable, deep water settings. With the current acoustic modem technology, underwater communications concentrate in the 5 to 80 kilo Hertz range. For instance, EvoLogics' modems may operate, according to the model, from 7 to 78 kilo Hertz [3]. All Teledyne Benthos' modems operate in three bands: 9-14, 16-21 or 22-27 kilo Hertz [4].

More particularly, we focus on software emulation of underwater acoustic wave propagation and software modulation and demodulation of underwater acoustic digital data signals in presence of mobility, with integration with other protocol layers. For underwater operation, mobility is relevant because there are underwater vehicles and environmental conditions cause displacements of sensors.

2.1 Related work

In shallow water, acoustic waves are severely affected by temperature, site-specific noise and multipath propagation due to reflection and refraction. The speed of sound in water varies according to the depth and is affected by temperature, salinity and pressure. Stojanovic and Preisig [5] reviewed conditions that impair underwater acoustic communications. They include attenuation, time-varying multi-path propagation, low propagation speed, noise, delay spreading and Doppler effect. The speed of acoustic waves is about 1500 meters per second [5] close to the ocean surface, which is more than four times faster than the speed of sound in air, but five orders of magnitude smaller than the speed of light [6]. Compared with electromagnetic and optical waves in terrestrial networks, the speed of acoustic waves is significantly lower. As a consequence, underwater channel communication is also affected by a severe Doppler effect.

Attenuation is captured by the Thorp model [7]. Harris and Zorzi [8] have developed a fourcomponent underwater acoustic communication model for the network simulator NS2 [9]. The four components of the model are *propagation*, *channel*, *physical* and *modulation*. The propagation model follows the work of Stojanovic [10].

EvoLogics S2CR is an underwater acoustic modem emulator [3, 11]. It does physical layer and data-link layer emulation. Other software emulation works include Nautilus, of Masiero *et al.* [12], a channel model including neighbor set calculation, collisions and propagation delays, of Cnar and Orencik [13], the World Ocean Simulation System (WOSS) library [14], a model developed by King [15] for the OMNeT++ simulation environment [16], and a model for the OPNET environment by Llor *et al.* [17, 18].

2.2 Main results

We have developed a solution leveraging the simulation work of Borowski [19]. The physical layer is modeled using Matlab functions. They are compiled into a dynamic library that makes them invokable in the OMNeT++ simulation environment. The latter can address better the protocols placed in the link layer and above. Our physical layer model mainly takes into account attenuation and noise. Attenuation is frequency and propagation distance dependent. We model attenuation, and its effect, on a modulated Phase Shift Keying (PSK) signal as a function of distance and frequency. Noise is frequency dependent. We implement the effect of noise on a PSK signal as a function of frequency.

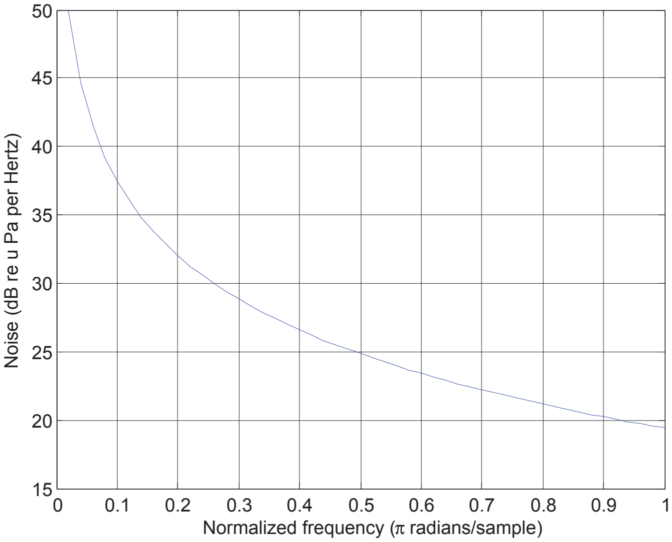

Figure 1: *Noise versus normalized frequency, in π radians/sample (f_s is 100 K sps).*

Assuming a sampling frequency f_s of 100 K sps, Figure 1 plots the power of the noise as a function of the normalized frequency (i.e., the frequency actually goes from zero to 100 K Hertz).

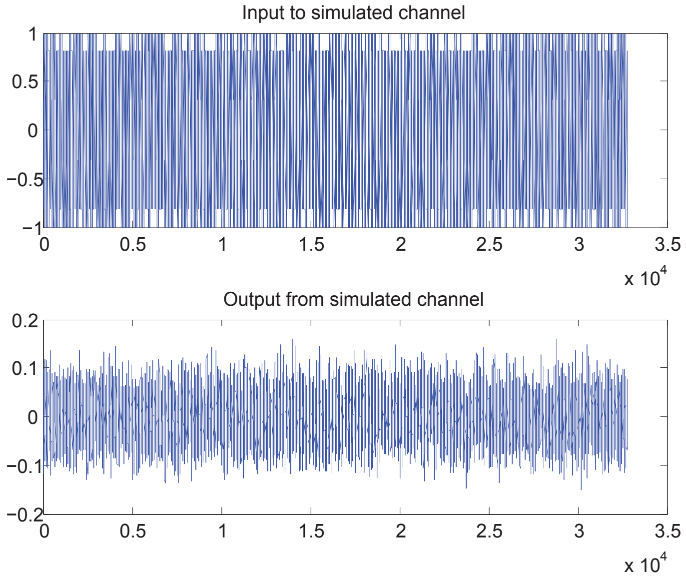

Figure 2: *Example input/output of simulated channel.*

Figure 2 shows an example signal before and after passing through the simulated channel.

Details of the research on this topic as well as our simulation results are described in [1]. Our paper discusses the attenuation and noise models adopted for this work, details of our physical layer simulation methodology, and the integration within the OMNeT++ environment.

3 Location-free routing in UASNs

UASNs consist of nodes equipped with acoustic communication capabilities. They are deployed underwater, at potentially different depths, to perform collaborative monitoring tasks [20]. Underwater nodes gather and send information to sinks. The latter are also equipped with radios to communicate with other network elements located on the water surface and on the shores. We review underwater routing related work and present a location-free routing protocol designed for UASNs.

3.1 Related work

Research on UASNs has been focusing on both the physical and link layers [10, 21]. However research on the network layer is still in an early stage. The design of efficient routing protocols should consider the limitations of the medium. The underwater acoustic channel is characterized by a high bit error rate, low data rate and large propagation delay, see Section 2.1. Underwater routing protocols must be energy-aware, since the deployment and maintenance of underwater devices are particularly difficult. UASNs are formed by nodes in constant motion that leads to continuous changes in the network topology.

Routing protocols for ad hoc networks are not suitable for underwater communications. Ad hoc network proactive routing protocols require a constant exchange of control information to keep the routing information up to date. In ad hoc network reactive protocols, the route discovery process is affected by an increased delay.

UASN routing protocols are based on greedy hop-by-hop packet delivery [22]. In contrast to end-to-end routing, greedy hop-by-hop routing selects, as next hops, one-hop neighbors offering positive progress toward a sink. Greedy hop-by-hop routing, however, do not guarantee finding a path toward the sink. That is, data packets may reach a node with no positive progress. This problem is known as *communication void*.

UASN routing protocols can be classified as *location-based* or *location-free*. Location-based protocols assume that every node knows its own and sink geographical positions. As a main drawback, finding the location information of nodes is a challenge due to the inapplicability of GPS under the water. Location-free protocols can be divided to pressure-based and beacon-based categories. In pressure-based routing protocols, the depth information (i.e., pressure) is used to determine a positive forwarding area. Beacon-based protocols use beacon messages that contain information about sink reachability, e.g., distance in hops. Greedy routing protocols in UASNs do not take into account the quality of the links.

3.2 Main results

We present a new location-free UASN routing protocol. For the purposes of packet forwarding in direction of the sink, every node selects a next hop according to link-state metrics. Figure 3 depicts an example. To prevent communication voids, the next hop is selected such that progress toward the sink, $S1$ in Figure 3, is guaranteed. It is assumed that nodes are equipped with pressure measurement sensors. Every node ranks the quality of the path that it offers toward the sink. Path quality is a redundancy metric. Every node generates beacon messages that include path quality, hop count toward the sink and pressure. Sinks generate beacon messages with path quality equal to one and hop count and pressure equal to zero. For an underwater node, the initial path quality is equal to zero. Upon receiving a beacon message, the receiver updates its path quality and hop count state.

In Figure 3, arcs are labeled with beacon messages, parameterized with path quality, hop count and pressure. For instance, after receiving beacon message $[1,0,p_{S1}]$ from sink $S1$, underwater nodes v_a and v_b generate a new beacon message with path quality and hop count equal to one. The one-hop neighbor with lowest hop count value is selected as next

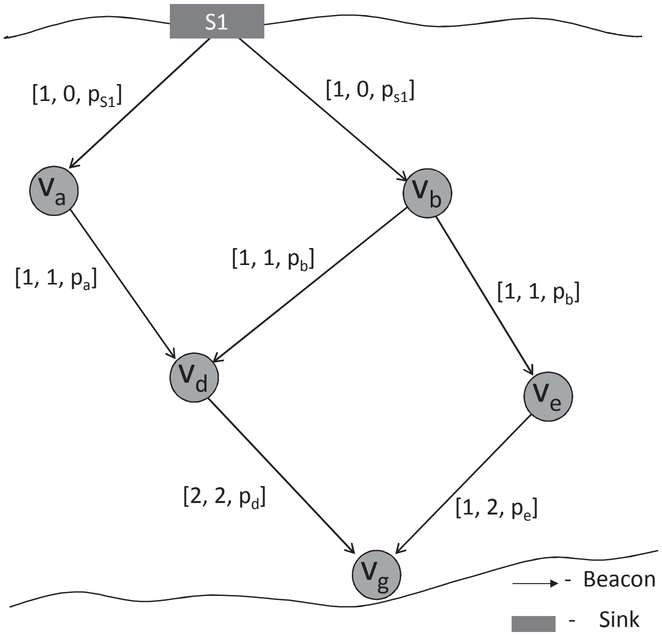

Figure 3: *Arcs are labeled with beacon messages, parameterized with path quality, hop count toward the sink and pressure.*

hop for packet forwarding. In case of a tie, the greatest path quality node is selected. If the tie persists, the lowest pressure node is selected. Initially, nodes v_a and v_b generate beacons with zero path quality and infinity hop count. After receiving the message from $S1$, both update their state. Node v_a generates beacon message [1,1,p_a]. Node v_b produces [1,1,p_b]. Node v_d receives beacon messages from both v_a and v_b. The path quality of v_d becomes two, i.e., the sum of the path quality of neighbors v_a and v_b. Assuming that it has the lowest pressure, node v_d selects v_a for packet forwarding. It is the neighbor closest to the surface. To reach the sink, v_g has two equal hop count options: v_d and v_e. Node v_d is selected because it has the highest path quality.

The routing protocol is loop-free and comprises a recovery mode handling network topology changes, e.g., when links are broken. Details of the research on this topic as well as our simulation results are described in [2].

4 Future work

Future work will focus on the one hand on extensions of the research already conducted and detailed in reports [1] and [2] and on the other hand on the main themes of our core research proposal on UASNs.

4.1 Physical layer

As a continuation we will investigate *Adaptive mobile underwater communications*. That is, the signal frequency and bandwidth are adjusted according to the separation distance between a transmitter and a receiver. Determination of frequency and bandwidth, as a function of the separation distance, has already been implemented and simulated in OMNeT++ by our research group. We will develop an OMNeT++/Matlab simulation comparing the performance of a model where frequency and bandwidth are fixed with a model where frequency and bandwidth are adapted to the separation distance between two nodes.

4.2 Underwater routing

Optimized link-state Routing (OLSR) is an adaptation of the link-state principle to ad hoc networks. OLSR comprises optimization for ad hoc networks, such as partial link-state dissemination. Hierarchical OLSR has been defined to address scalability and heterogeneity in ad hoc networks. The network is organized into hierarchical clusters interconnected by cluster heads. Routing metrics, other than hop count, have been integrated to OLSR. To deal with unreliability and low bandwidth, multi-path routing has been introduced. A gateway-based model was created to interconnect OLSR ad hoc networks with the Internet. For reasons discussed in Section 3.1, OLSR, a proactive protocol, is not directly applicable to UASNs. Several link-state routing related ideas are, however, relevant to UASNs.

We will carry on with the adaptation of link-state routing ideas to UASNs. Link-state routing has potential because UASNs and terrestrial ad hoc networks share several characteristics and requirements. In particular, UASNs are heterogeneous. They are made of surveillance sensors, submarines and underwater vehicles. They have interoperability needs with shore and water surface network elements, ships, aircraft and satellites.

4.3 Opportunistic communication

UASNs employ acoustic signals for communications. Meant to monitor large 3D underwater spaces, they are deployed at various depths. They differ from terrestrial sensor networks, which are modeled in the 2D plane and positioned within a geographically constrained area. Topology control approaches involving optimal node deployment to 1) achieve *coverage* and/or *monitoring* of a given region (i.e., every point in the region is within range of a sensor), 2) maintain network *connectivity* (i.e., any two nodes can be connected by a directed communication path), 3) attain *optimal cost routing* for reliable communication (i.e., identify a reliable minimum cost path to transmit data), and 4) obtain *localization*, are extremely hard in the underwater setting. Efficient *space monitoring*, *connectivity*, *routing*, and *localization* are important tasks whose resolution affects overall network performance. Their effect is particularly pronounced in underwater settings where sensors can be expensive and must also be able to operate in a dynamic, adverse environment.

Major challenges in UASNs include the unreliable acoustic channel, presence of voids, ocean currents, and limited resources (bandwidth and energy). We will explore *opportunistic communication*, which makes use of whichever link and/or node happens to be available and error-free for a given transmission. Specific phenomena in underwater settings, like downward and/or upward refraction, surface channels, convergence and shadow zones, and hydraulic pressure, which have never been thoroughly investigated in the literature, will be explored. Traditional propagation models are omnidirectional with the signal expanding from the source in all directions. In addition, we will study the above mentioned topology control problems in a directional propagation model based on underwater directional beacons. The propagation of such beacons is delimited by a directional cone parametrized by beam-width (or spherical angle), communication range, and sensing range. Potential advantages include reduced energy consumption (note that acoustic communication consumes much more energy than radio-frequency communication), lowered interference, tighter security, and improved routing efficiency due to the limited beam-width. Using directionality in an opportunistic manner (when and if it is possible) one may improve reach and performance, e.g., in cases where you may have a priori knowledge where the target node might be you may be able to reach farther with less hops and less energy. Therefore in conjunction with the physical characteristics of the environment it could complement traditional routing and improve performance.

4.4 Additional details

OMNeT++/Matlab simulations are being built, recreating the conditions of UASNs. The strengths and weaknesses of routing protocols for operation in this context are being uncovered and analyzed. Areas for possible performance improvements for UASNs are identified. Possible adaptations may apply to the control information (the rate at which it is produced, the content, its coding), network topology (cluster formation algorithms), routing (route construction algorithms, routing metrics, reliability) and forwarding (use of the routing information). We investigate the integration of topology control ideas into the underwater environment.

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