The Sound of Communication in Underwater Acoustic Sensor Networks

(Position Paper)

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Abstract. Underwater environments have never been much of a constraint to the rich animal life they support at all depths of our seas and oceans. Indeed, nature has taken advantage of this environment to develop a rich variety of efficient communication strategies through evolutionary change and adaptation. The wealth of knowledge to be discovered will continue to dazzle and fascinate the world. For underwater sensor network communication, acoustic signalling is the preferred choice for designers because sound propagation is the most efficient when compared to other forms, like thermal, light, and electromagnetic. It is within this *acoustic* environment that researchers have to innovate and develop new ideas and methodologies so as to advance the state-of-the-art. In this paper, several fundamental issues and connections are discussed that arise in the study of underwater wireless sensor networks. A variety of ideas and solutions for further research is proposed and fundamental issues in topology control, directional underwater transducers, and monitoring and surveillance are discussed.

Keywords: Directional hydrophone and vibrator
Monitoring and surveillance · Neighbour discovery
Underwater acoustic communications

1 Introduction

Sound is very important for communication in the animal world. It helps animals to become aware of events that occur all around, regardless of where attention is focused. With respect to their land counterparts, sea mammals are even more dependent on sound for communication and sensing because of the special circumstances involved in the nature of signals underwater affecting the propagation of light, smell, and other senses. One must take into account that light propagation suffers from scattering due to reflection and refraction. Smell

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is affected by molecular diffusion due to temperature, viscosity of the fluid, and size of the particles. As a consequence, sight and smell could be ineffective and rather much less suited for communication in the seas when compared to sound. Sound has another advantage because water molecules lose less energy as they vibrate. This paper explores how sound can be used to effectively communicate and build underwater networks. In Sect. 2, we introduce the nature of sound in the underwater environment. We explore the transmission of messages using sound in Sect. 3. A model for directional underwater communications is presented in Sect. 4. We conclude in Sect. 5.

2 Nature of Communication Underwater

You can calculate the speed v (m/s) of sound by taking the square root of the ratio of the pressure p (Pa) of the medium, inside which it travels, divided by the density ρ (kg/m^3) of this medium, namely

$$v = \sqrt{\frac{p}{\rho}} \text{ m/s.} \tag{1}$$

In the air, it is approximately only 343 m/s (at sea level). However, despite the fact that the propagation of sound underwater is affected by temperature, salinity, hydrostatic pressure and other factors, its speed in the ocean varies from 1,450 m/s to 1,540 m/s. It is more than four times higher than its speed in the air. Also note how pressure affects the speed of sound. Approximately 1,6 m/s per 100 m downwards is added to the velocity due to the increase in hydrostatic pressure.

Mammalian evolution has created numerous adaptations so as to exploit the propagation of sound underwater. Acoustic communication in the seas is entirely different from the more familiar terrestrial. Moreover, in marine life, mechanisms used to produce sound vary widely even from one family of sea animals (such as whales, dolphins, and porpoises) to another. This is documented extensively in the scientific marine biology literature. For example, it is well known that the humpback whales are producing regular and predictable sounds known as *songs* to communicate male fitness to females. The clicking sequences of dolphins and sperm whales are thought to be individualized rhythmic sequences communicating the identity of a single mammal to others in its group. They allow groups to coordinate foraging activities. Furthermore, communication can reach large distances with sperm whales being the undisputed vocal champions that can give a powerfully deafening directional sonar of 240 dB.

One cannot but marvel at the astonishing variety of sound based communication mechanisms that have evolved throughout sea life to communicate, attract mates, defend territory, sense surroundings and find food [6]. (See Ref. [18] where you can play recordings of all kinds of underwater animals, from whales and shrimps to oysters.) Although whales can communicate long distance with their powerful sounds, at the opposite scale Patek [20,25] reports that the *spiny lobster* emits Near Field Communication (NFC) signals (that propagate no more than a meter) every time it throws off its exoskeleton. The very unique sound it generates (by using its body as a violin) protects the *naked* lobster against its enemies while at the same time the short distance of propagation prevents it from advertising its presence further away!

3 Transmission of Sound

What technical issues do we encounter in transmitting messages underwater? How can we take them into account and at the same time improve our communication capabilities? We discuss how sonar measurements are made underwater as well as the impact of waveguides (communication tunnels) for connectivity.

3.1 Sonar Measurements

Sonar (also called *echolocation*) refers to the principle of detecting and localizing objects by sound. When referring to animals, it is also called *biological sonar* or *biosonar*. SONAR is an acronym for SOund Navigation And Ranging [3]. It is a technique that uses underwater sound propagation to navigate, communicate with or detect objects (such as submarines and mines) on or under the surface of the water by projecting sound and detecting the echoes from the objects.

The key to measuring the intensity and pressure of acoustic waves is based on using the concept of decibel (dB). Since in underwater acoustics, the primary interest is often in ratios rather than in absolute quantities this gives a convenient way for expressing changes (usually large) in pressure. Given two powers P_1 and P_2 (Watts), with power ratio P_1/P_2, we use the *decibel* expression $10 \log_{10} (P_1/P_2)$ dB. When an acoustic wave propagates in a medium, acoustic energy is being transmitted. The amount of energy per second crossing a unit area is called the *intensity* of the wave. The unit of intensity in underwater acoustics is defined as the intensity of a plane wave having a pressure p of one micropascal (μPa). The relationship between acoustic pressure p and intensity I (Watts/m^2) is $I = p^2/(\rho v)$ Watts/m^2, where ρ (kg/m^3) is the density of water and v (m/s) is the speed of sound.

The intensity ratio I_1/I_2 is defined in decibels similarly to the power ratio, i.e., the intensity ratio in dB is equal to $10 \log_{10} (I_1/I_2)$ dB. The basic measurement in acoustics is based on pressure and not on intensity. Most hydrophones used in underwater measurements are sensitive to pressure, particle velocity, or pressure gradient. It follows from from the above that the pressure ratio in decibels is expressed as $20 \log_{10}(P_1/P_2)$.

3.2 Impact of Temperature and Pressure on Sound

Underwater, propagation of sound is three dimensional. It propagates in all directions from its source. During transmission sound dissipates. Understanding its behaviour is complicated by such features as suspended particles, air bubbles, plankton, and even the swim-bladders of swimming fish.

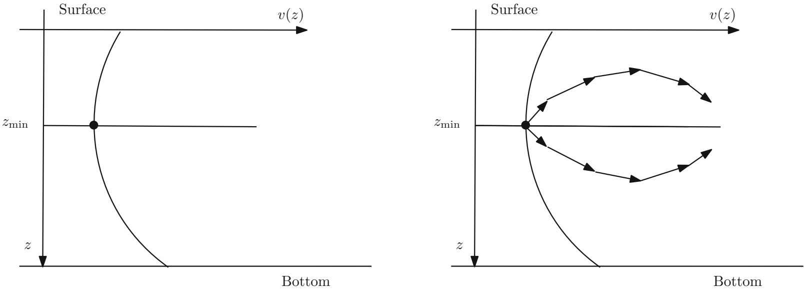

Fig. 1. *Left:* Diagram of the speed of sound $v(z)$ as a function of the depth z. *Right:* Due to refraction, a sound waveguide is formed whose walls delimit the propagation of sound when the emitting source is placed at depth $z_{\min}$.

The speed of sound in the ocean varies, see Eq. (1). It depends on temperature, salinity, pressure and other factors. Note that the pressure $p(z)$ (μPa) is monotone increasing as a function of the depth z(m). Also temperature affects the speed $v(z)$ of sound, as a function of the depth z. The interplay of these two factors affect $v(z)$ that has a representation resembling the plot depicted in the left part of Fig. 1. Closer to the surface, the speed $v(z)$ of sound is more affected by temperature. It decreases as we move deeper. As we move even deeper, the impact of pressure overtakes temperature. The speed of sound increases. Eventually, temperature and pressure balance out at a certain depth $z_{\min}$. The resulting speed of sound $v(z_{\min})$ at $z_{\min}$ is the minimum possible. This depth $z_{\min}$ also depends on the oceanic temperature. It can be up to 2 km in warmer waters while it is closer to the surface in the Arctic.

3.3 Impact of Refraction and Waveguides

Sound propagating in the ocean can sometimes be detected thousands of kms away from the source. Does the ocean contain a channel (or *acoustic waveguide*) through which sound can propagate with little attenuation? Indeed, it is not difficult to speculate that a natural channel is formed between the surface of water and bottom of the ocean. But what mechanism do sound waves obey in such long-distance propagation? The basic principle is that transmission of sound along a waveguide is based on the reflection of waves along its boundaries which prevents scattering. It would seem as if sound propagates along a *narrow tube* reflecting along its boundaries. But how are such gigantic waveguides formed underwater and where are its boundaries?

It turns out that refraction plays a crucial role in the formation of waveguides. Assume a sound source placed at depth $z_{\min}$, see right part of Fig. 1. Consider the sound beams emanating from it. Because of refraction, the propagation of the sound depends on the angle of the beam with respect to the horizontal. A beam propagating along a horizontal line is straight. A beam leaving $z_{\min}$ at an angle bends. However, since the speed of sound increases both up and down from the point $z_{\min}$, sound beams bend towards the horizontal. As a consequence this gives rise to a waveguide whose *walls* are formed by the layers of water at the depths where the sound beams reflect. For additional details see [2] (Chap. 3: The Oceanic Phone Booth) as well as Porretta's recent thesis [21].

To understand better the formation of waveguides, let $v(0)$ and $v(f)$ be the speeds of sound in the surface and bottom of the sea, respectively. It turns out that two types of waveguides may be formed depending on the relative sizes of the speeds $v(0)$ and $v(f)$.

Case $v(f) > v(0)$*:* This usually occurs in deep water. On the one hand, when the water surface is calm the sound is reflected from the surface but is refracted at sea bed. In fact one can use Snell's law to determine what portion of the sound beam is *captured* by the channel [2]. On the other hand, when the water surface is rough the sound scatters from it. The rays leaving the surface at large angles reach the bottom and are absorbed there. However, because of refraction the channel captures those rays that do not reach the rough surface [2].

Case $v(f) < v(0)$*:* This usually occurs in shallow water. In this case the sound refracted at the bottom does not reach the surface [2].

Schmidt and Schneider [10,23,24] documented the existence of a waveguide in the Beaufort Sea, called the Beaufort Lens. Due to a flow of warm water entering through the Bering Strait, from the Pacific Ocean. A sound speed minimum is created at low depth, around 80 m. Sound energy is trapped in the resulting waveguide. Long range (100 km) communication, without ice interaction, is possible using the waveguide.

The principle can be studied through simulation. Figure 2(Left) shows a Sound Speed Profile (SSP), artificially created to better illustrate the idea. It plots the speed of sound (x-axis) as a function of depth (y-axis). There is a sound speed minimum at 500 m deep. This minimum creates a waveguide in which the acoustic energy propagates without interaction with sea surface or sea bed. Figure 2(Right) shows the result of a BELLHOP [22] simulation of the

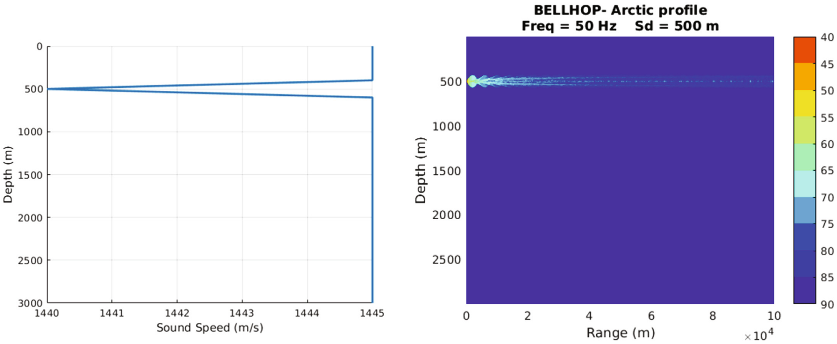

Fig. 2. *Left:* Sound speed profile with local minimum. *Right:* Transmission loss (dB) versus distance and depth, at 50 Hz and from zero to 100 km.

waveguide at the acoustic signal frequency 50 Hz. The source-receiver separation distance is from zero to 100 km. The x-axis represents range (m). The y-axis represents depth. A signal source is placed on the left, at range zero and depth 500 m. On a dB scale, color-coding represents signal attenuation as a function of location. In underwater, attenuation is proportional to frequency. Hence, attenuation is weaker on the left, staring at 70 dB on short range. The simulations demonstrate that signals propagating through a waveguide theoretically persist across long distances.

4 Directional Underwater Transducers

Directional antennae are widely used in wireless communication. They are versatile. They improve overall energy consumption [14]. This is rather easy to motivate. The transmission cost is proportional to the area covered by the antenna. Thus, the energy cost of an omnidirectional antenna with range r (m) is proportional to the area of a disk of radius r, that is, πr^2 m^2. By comparison the signal from a directional antenna of beam-width ϕ radians reaches much further, with the same energy consumption, namely it has range $r\sqrt{2\pi/\phi}$ m that, depending on the beam-width ϕ, can be significantly larger than r. They have numerous applications. They may enhance network capacity [9,26], reach further than omnidirectional antennae for detection and surveillance purposes, improve topology control and stability [8], and offer the potential for mitigating various security threats [11], just to mention a few applications.

A significant amount of research has been dedicated to the 2D model of directional antennae. In this model, the antennae are located in a planar terrain. To establish a network, antennae need to communicate with each other. To this end, two basic antennae communication models are employed. Consider two directional antennae: a sender and a receiver. In the *symmetric* model, communication is possible if the sender and receiver are within the range (determined by respective lobes) of each other, see [1,17]. In the *asymmetric* model, the sender can transmit directly a message to the receiver (provided the receiver is within the range of the sender) but the receiver may not be able to send directly a message to the sender, see [4,7,13,16]. In a way, the asymmetric model is less rigid than the symmetric one, but the receiver must seek a (alternate) path in the network if it also wants to talk to the sender.

4.1 3D Underwater Transducer Model

Underwater communications differ from classical wireless. Rather than electromagnetic waves, mechanical acoustic waves are used. The transducers, converting electrical energy to mechanical energy and vice versa, are vibrators and hydrophones. Transmission is done with mechanical vibrators. Reception is done with mechanical hydrophones. Hereafter, we discuss a 3D underwater transducer model. We identify vibrators and hydrophones. We model a *three dimensional* directional underwater transducer as a spherical sector of solid angle Ω (Fig. 3,

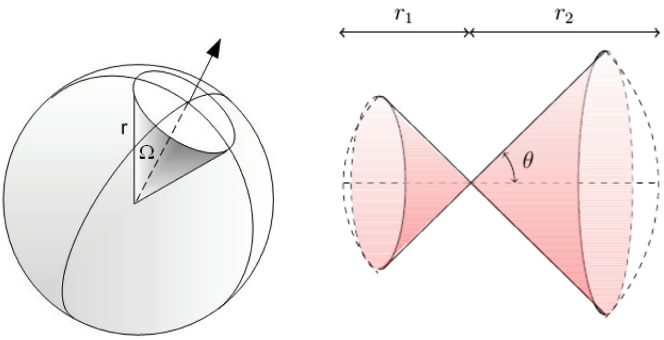

Fig. 3. Spherical underwater transducer radiation patterns. Solid (represented by Ω) and apex (represented by 2θ) angles in the 3D directional antenna model. The antenna in the left picture has a single lobe while in the right picture it has a double lobe.

left) and apex 2θ (Fig. 3, right). The *solid* angle Ω of a solid spherical sector is defined as the ratio of the area of the spherical surface and square of the radius of the sphere of which it forms part. The *apex* angle of a spherical sector with solid angle Ω is defined as the maximum planar angle between any two generatrices of the spherical sector. It is usually represented by 2θ, see [12] for additional details. The apex 2θ and solid angle Ω are related by the following important identity due to Archimedes. $\Omega = 2\pi(1 - \cos\theta)$; this Formula gives a method to compute a 3D angle with the help of a 2D angle.

4.2 Communication Model

How can we model communication using directional underwater transducers? We distinguish two types of connectivity: *symmetric* and *asymmetric*. In symmetric communication, two underwater transducers communicate if they are within range of each other, see Fig. 4(Left). This also means they can send messages directly to each other. Contrast this with asymmetric communication (Fig. 4(Right)) in which a vibrator S can talk to a hydrophone R only if there exists a sequence of $(\mathit{vibrator}, \mathit{hydrophone})$ pairs $S \rightarrow S'$ such that $S := S_1 \rightarrow S_2, S_2 \rightarrow S_3, \ldots, S_{k-1} \rightarrow S_k := R$ and moreover so that each hydrophone in this sequence is within the range of a vibrator. Thus, to establish bidirectional communication between S, R in the asymmetric communication model not only a *path* must be found between source S and destination R; in addition, a *path* must be found in the reverse direction from destination R to source S. Despite this difficulty it is still possible to provide algorithms that can establish bidirectional communication [4,7,13,16] with constant stretch factor.

4.3 Neighbour Discovery

How does a underwater node discover its neighbour(s)? The neighbour discovery process usually entails the exchange and subsequent confirmation of identities

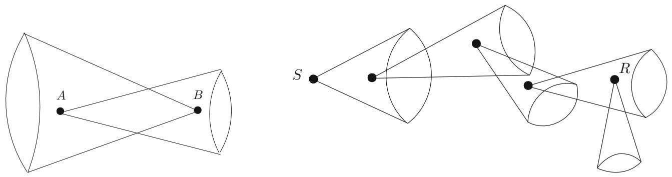

Fig. 4. Left: Symmetric communication with two directional underwater transducers centered at points A and B. Right: Asymmetric communication with directional underwater transducers: A directed communication path from vibrator S to hydrophone R.

between two adjacent nodes so that they can identify each other. To achieve this, omnidirectional underwater transducers must be, at a minimum, within range of each other (so that they can receive each other's messages). Thus, neighbour discovery for directional underwater transducers in the *symmetric* model requires not only that they must be facing each other but also be within range of each other. In the *asymmetric* model a communication path must be found between a sender and a receiver. Regardless of the communication model being used, the underwater nodes must execute an algorithm to discover their neighbour(s). To simplify matters, let us look first at 2D. Consider two directional nodes u and v with beam-width ϕ_u and ϕ_v, respectively. To communicate their underwater transducer must be facing each other. For each node u, let d_u be an integer delay parameter and k_u be defined so that $\phi_u = \frac{2\pi}{k_u}$ and consider Algorithm 1.

Algorithm 1. Underwater Transducer Rotation Algorithm $ARA(d_u, k_u)$

```
Start at a given orientation
while true do
    for $i \rightarrow 0$ to $d_u - 1$ do
        Send messages to neighbour(s)
        Listen for messages from neighbour(s)
        Rotate transducer beam one sector counter-clockwise
```

It can be shown (see [5] for details) that for a set S of synchronous nodes by appropriately choosing (either deterministically or at random) the delay d_u, for $u \in S$, Algorithm 1 ensures that every pair of underwater transducers within range will discover each other.

An approach to solving the neighbour discovery problem for underwater nodes is to adapt the previous approach, except that underwater transducer rotations must be done in 3D. The key idea is to use a partition of 3D space in a geodesic grid Moreover, like in Algorithm 1, underwater transducers would somehow have to rotate over a well-defined domain specified by a geodesic grid. The rotation mechanism (speed and direction of rotation) may depend on some knowledge of the environment and on the depth (see [15] for a related study).

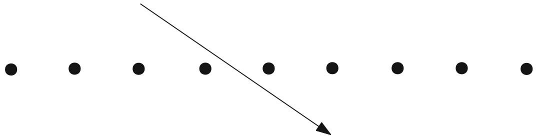

Fig. 5. An array of hydrophones and a passing underwater autonomous vehicle.

4.4 Monitoring and Surveillance

A potential application would be in establishing a wireless underwater networked system of communicating nodes to form an effective monitoring and surveillance network. Figure 5 depicts a linear array of underwater hydrophones and a passing autonomous vehicle. Each hydrophone has the ability not only to detect a passing autonomous vehicle, but also to discover its neighbours and transmit messages to them (other nodes within its range). Further, and unlike the scheme proposed by [19] which is static and not immune to transducer failures, the resulting array is dynamic and fault tolerant thus also adapting to a changing communication environment.

5 Conclusion

Research in UWANs requires a multidisciplinary approach involving scientists and engineers of widely varying academic backgrounds, experience and expertise. In this paper we looked at some characteristics of underwater communication and how they can be used so as to develop methodologies for better and more reliable connectivity. Further, we discussed the possibility of designing a wireless networked system based on underwater hydrophones to support monitoring and surveillance services. The ultimate goal would be to aid the design of surveillance underwater wireless acoustic networks in (harsh) underwater environments.

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