A Survey on Statistical Channel Modeling for Underwater Acoustic Communications

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Abstract—Underwater acoustic (UWA) channel is one of the common systems for wireless underwater communication. However, the underwater environment poses significant challenges to reliable and efficient communication. This paper is a survey on channel modeling for UWA communications. We investigate various UWA channel modeling approaches that incorporate both large- and small-scale fading effects and provides a comprehensive summary of the key findings.

Index Terms—Underwater acoustic communication, ray tracing, statistical channel modeling.

I. Introduction

Oceanic channels represent a particularly intricate medium for any form of signal transmission, and their inherent complexity presents substantial challenges. Among the various methods, acoustic signals have proven to be suitable for underwater transmission [1], [2]. However, underwater acoustic (UWA) channels are highly complex and dynamic. Factors such as water temperature, salinity, current, sea surface conditions, and seabed composition can affect signal propagation. The UWA channel can vary significantly over time due to the factors mentioned above. Understanding these effects allow for the design of more robust and reliable communication systems. Modeling these changes enables the development of adaptive systems that can respond to fluctuations in characteristics of the channels, maintaining optimal performance. In the past decades, driven by an expanding demand for wireless underwater connectivity and influenced by the advent of novel digital communication methodologies, UWA communications have evolved beyond their primarily military applications [3]. According to [4], the acoustic signals undergo a multitude of loss phenomena such as absorption, scattering, multipath propagation, and Doppler shifts. To precisely understand and estimate the transmission pattern that acoustic signals are propagated through seawater, experimental modeling of the underwater channel needs to be carried out.

II. UWA Channel Modeling Approaches

In this section, we explore the various channel modeling approaches for the UWA communications. We begin by investigating deterministic channel modeling using a ray tracing method. Subsequently, we present several fading distributions in relation to the specific scenarios. Then, we investigate an integrated UWA channel simulator focusing on its underlying principles and application.

A. Deterministic Channel Modeling

The UWA channel has been modeled utilizing Bellhop which is a ray tracing-based toolbox [5] to provide an accurate deterministic picture and allocate the appropriate resources of the UWA communications for a given geometry and carrier frequency. To validate this modeling approach, we first define the large-scale multipath channel function experienced by a signal of frequency f as

$$H_{LS}(f) = \bar{H}_0(f) \sum_p h_p e^{-j2\pi f \tau_p}, \qquad (1)$$

where $\bar{H}_0(f)$ is the reference path, h_p is p-th path gain, and τ_p is p-th path delay. An often-used method for obtaining the large-scale components is to generate impulse responses for multipath channels by using ray tracing-based experimental tools. Then, these instruments simulate the propagation influences specific to a given channel geometry, with properties discerned from a variety of databases. Specifically, the source can designate the geographic coordinates of the desired channel location, prompting the simulator to query the databases for pertinent data such as measurements of sound velocity, bathymetry, and samples of bottom sediments. Insight into environmental conditions at the experimental site informed the repeated execution of the Bellhop model, leading to the generation of a collection of channel responses. This ensemble is subsequently employed to ascertain the statistical characteristics of the channel. The findings derived from the

Bellhop channel simulator exhibited statistical attributes that were analogous to those observed through direct experimentation, highlighting the simulator's ability to replicate certain real-world dynamics.

B. Statistical Channel Modeling

Large-scale variations are modeled as a consequence of system displacements that cannot be predicted using the nominal system geometry. In this regard, despite the elaborate experimental tools for realizing the UWA channel, it is still important to establish a mathematically stringent model that encompasses physical characteristics of acoustic propagation in the underwater environment. Motivated by this, numerous studies have been implemented to statistically model the UWA channel. These studies are usually depend on the evaluation of acoustic data collected experimentally in a particular place. Some prior works considered Rayleigh, Rician, Nakagami-m, and log-normal fading distributions [6], [7] as proper matches for their measurements and particular scenarios. Specifically, Rayleigh fading is suitable for deep water. In contrast, it is appropriate to consider Rician fading in shallow water. Accordingly, statistical channel model of small-scale phenomena using the particular fading distribution is ambiguous by means of the numerous underwater scenarios. The diversity of the fading distributions arises from properties specific to individual experiments, such as the characteristics of the deployment site, the types of signals utilized for probing, and the temporal intervals during which the channel is under observation. Since only partial knowledge of the environmental conditions was used, an accurate agreement was not observed.

C. Integrated Deterministic and Statistical Channel Modeling

To incorporate the UWA channel knowledge of the environmental conditions, the efficient channel modeling in [8] was proposed considering not only the physical attributes of acoustic propagation but also the influences of inevitable stochastic channel fluctuations focusing on a small-scale, characterizes intrapath dispersion. This serves as an initial foundation from a statistical perspective, but it should be noted that this may not represent the most comprehensive understanding of the subject matter. Nevertheless, this analysis proves meaningful in the context of analyzing top-level system functions. Therefore, through this paper, we introduce the UWA channel modeling approach as presented in [8], which employs Bellhop. While the Bellhop-based algorithm offers realistic assessments for the standard properties of the channel, they do not incorporate the impacts of stochastic channel variations. Thus, it is more desirable to leverage the statistical channel modeling approach together with the Bellhop algorithm to accurately represent the inherent characteristics and the impacts of the inevitable random fluctuations in the UWA channels.

Due to the various properties in an underwater medium, an acoustic signal undergoes non-trivial effects caused by different phenomena. In this regard, it is important to consider the scattering effects in terms of intrapath delays and Doppler effects in the UWA channel environment. From [8],

TABLE I
UWA CHANNEL ENVIRONMENT TABLE.

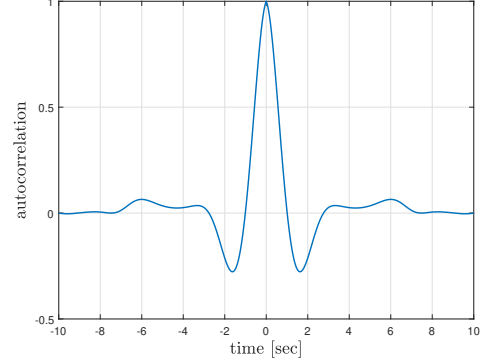| Range	1000 m	Coherence time	1 s
Source height	20 m	Delay spread	40 ms
Receiver height	50 m	Bandwidth	1 kHz, 10 kHz
Water depth	100 m	Carrier frequency	10.5 kHz, 15 kHz

Fig. 1. Autocorrelation of the small-scale coefficient with Doppler effects.

we define the overall channel incorporating large and small-scale coefficients as

$$H(f,t) = \bar{H}_0(f) \sum_p h_p \gamma_p(f,t) e^{-j2\pi f \tau_p}, \qquad (2)$$

where $\gamma_p(f,t)$ indicates the overall small-scale fading which involves Doppler effects as well as intrapaths defined as

$$\gamma_p(f,t) = \frac{1}{h_p} \sum_{i \geq 0} h_{p,i} e^{-j2\pi f \delta\tau_{p,i}}, \qquad (3)$$

where $h_{p,i}$ is the intrapath gain and $\delta\tau_{p,i}$ is the intrapath delay. Both the gain $h_{p,i}$ and the delay $\delta\tau_{p,i}$ are treated as stochastic variables, reflecting the random distribution of scattering points within a given scattering field. According to [8], time correlation is derived by combining the small-scale path coefficient with the Doppler effects. Hence, we have the autocorrelation function as

$$R_{\gamma_p}(\Delta t) = \mathbb{E}\left[\gamma_p(f, t+\Delta t)\gamma_p^*(f,t)\right]. \qquad (4)$$

This function captures the impact of motion within the scattering field, providing a comprehensive understanding of the underlying dynamics. Fig. 1 shows the autocorrelation function using the parameters in Table I. As a result, we obtain the coherence time $T_c \approx 1$ s by taking the zero-crossing point within the given setting. It is worth noting that the main lobe of the surface component, which is governed by the Doppler factor, becomes progressively narrower with each subsequent surface encounter.

III. SIMULATION AND LIMITATIONS

Incorporating the fading effects, we establish the integrated channel simulator in Section II-C. Since the delays are entangled with the bases in the frequency domain, the corresponding impulse responses can be accurately determined
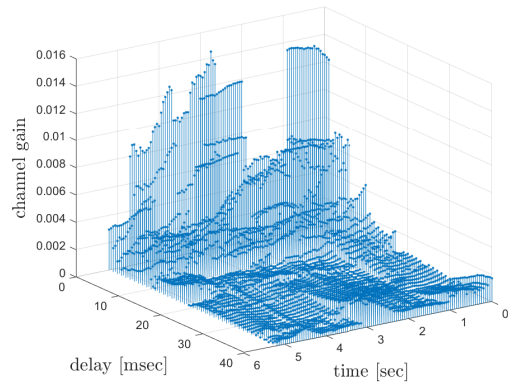
Fig. 2. Time-delay underwater acoustic channel impulse response with 1 kHz bandwidth.
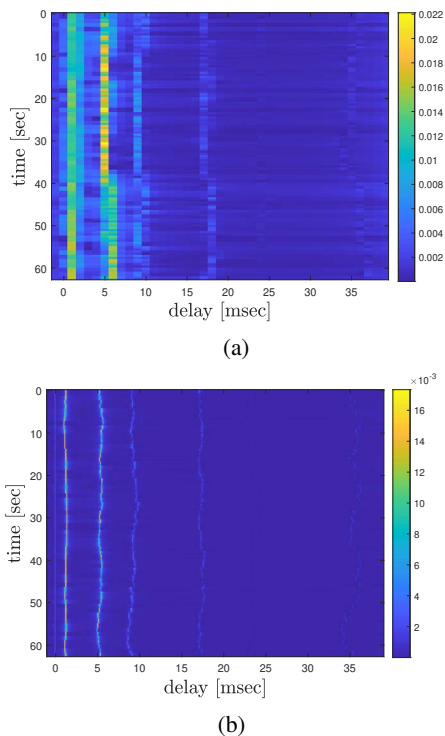

(a)

(b)

Fig. 3. Time evolution of the magnitude impulse response with (a) 1 kHz bandwidth, (b) 10 kHz bandwidth.

by isolating their delay times. Consequently, this approach enables us to derive the delay- and time-variant channel $H(\tau, t)$, which is our metric for the simulations. To verify the integrated simulator, we conduct experiments to observe the channel gains in time-delay domain using the given environment setting in Table I. Fig. 2 illustrates the channel gain with 1 kHz bandwidth. We observe that the multipath channels are generated with their propagation properties in the given underwater environment. It is worth noting that the presented channel modeling offers an intuitive technique for characterizing multipath channels. Furthermore, it establishes a comprehensive framework for designing UWA communication systems, aligning with both theoretical and practical considerations. Fig. 3(a) illustrates the channel response by

reproducing the result of Fig. 2 with longer observation time. The corresponding channel response possesses a relatively wide resolution due to its 1 kHz bandwidth, it illustrates a broad region depicting the relationship between delay and time evolution. However, when considering 10 kHz bandwidth, as represented in Fig. 3(b), the channel response exhibits finer resolution compared to 1 kHz bandwidth in Fig. 3(a). These results imply that the integrated UWA channel simulator is capable of creating the UWA channels which are consistent with our intuition. Therefore, this approach can be used most effectively and accurately in the UWA communication among suggested approaches. However, it does not incorporate the surface curvature and the phenomena of breaking waves. In addition, it assumes Gaussian-distributed intrapath delays of the scattered paths. Nevertheless, this UWA simulator approach impacts with the given geometry and a wide range of frequency. Therefore, it is the effective and analytical channel modeling method of a class of the UWA channels.

IV. CONCLUSION

In this paper, we investigated a variety of UWA channel modeling approaches, which incorporate both large- and small-scale fading effects. It is worth noting the importance of accurate channel modeling for designing reliable and efficient underwater network. With the integrated UWA channel simulator, we provided a comprehensive summary of the results and significant contributions of the research. The simulation results showed that the integrated simulator provides effective channel models, yielding significant insights into the analysis of top-level systems for the UWA communications.

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