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# Overview of channel models for underwater wireless communication networks

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ABSTRACT

Acoustic communication in Underwater Wireless Communication Networks (UWCNs) has several challenges due to the presence of fading, multipath and refractive properties of the sound channel which necessitate the development of precise underwater channel models. Some existing channel models are simplified and do not consider multipath or multipath fading. In this paper, a detailed survey on ray-theory-based multipath Rayleigh underwater channel models for underwater wireless communication is presented and the research challenges for an efficient communication in this environment are outlined. These channel models are valid for shallow or deep water. They are based on acoustic propagation physics which captures different propagation paths of sound in the underwater and consider all the effects of shadow zones, multipath fading, operating frequency, depth and water temperature. The propagation characteristics are shown through mathematical analysis. Transmission losses between transceivers are investigated through simulations. Further simulations are carried out to study the bit error rate effects and the maximum internode distances for different networks and depths considering a 16-QAM modulation scheme with OFDM as the multicarrier transmission technique. The effect of weather season and the variability of ocean environmental factors such as water temperature on the communication performance are also shown. The mathematical analysis and simulations highlight important considerations for the deployment and operation of UWCNs.


## 1. Introduction

Underwater Wireless Communications Networks (UWCNs) are constituted by devices such as sensors and Underwater Autonomous Vehicles (UAVs) that interact together to perform specific underwater applications such as collaborative monitoring over a given volume of water [1]. Underwater acoustic communication in these networks is an important challenge due to the presence of fading, multipath and refractive properties of the sound channel. Therefore, for an efficient deployment of these networks, the underwater channel characterization is absolutely necessary. Some existing simple channel models only distinguish between shallow (depths lower than 100 m) and deep waters (depths more than 100 m) and do not consider multipath and fading effects. However, the underwater communication is severely affected by different propagation phenomena as well as by the time-dependent variations of the channel.

In this paper we provide a comprehensive characterization of the underwater wireless channel and discuss the research challenges for an efficient communication in this environment. We present a complete survey on ray-theory-based multipath Rayleigh underwater channel models for shallow and deep waters. These models are based on acoustic propagation physics. They capture not only different propagation paths of sound in the underwater but also other effects such as multipath fading, operating frequency, depth, water temperature as well as the existence and effects of the shadow zones. The effect of seasons and the variability of ocean environmental factors, e.g., water temperature, on the communication

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performance are also investigated. The bit error rates and maximum internode distances are studied by considering a 16-QAM modulation scheme with OFDM as the multicarrier transmission technique. The mathematical analysis and simulations carried out in this paper reveal that underwater communication is severely affected by physical and chemical properties of the water, especially by the depth of transceivers and by water temperature. Our results highlight important considerations for the deployment and operation of UWCNs.

The paper is structured as follows: In Section 2 we discuss the related work about underwater channel modelling. In Section 3 we introduce the sound propagation in the underwater and focus on transmission loss as the quantitative measure in the reduction of sound intensity between two points. The characteristics of the underwater channels are described in Section 4. In Section 5, the effects of variations in water temperature are analyzed. Finally, Section 6 discusses the research challenges for UWCNs and concludes this paper.

## 2. Related work

Ray theory and the theory of normal mode are very effective methods for channel modelling. Ray-theoretical models calculate the transmission loss on the basis of ray tracing, whereas the normal-mode solutions are derived from an integral representation of the wave equation. The normal-mode approaches tend to be limited to acoustic frequencies below 500 Hz due to computational limitations (and not due to the underlying physics). Specifically the number of modes required to generate a reliable prediction of the transmission loss increases in proportion to the acoustic frequency [2]. Ray theory is very useful for the description of sound propagation at high frequencies in the underwater.

Some simple underwater channel models already exist where the transmission loss is related to the distance as in Thorp's equation [3] or use a propagation loss formula combined with a stochastic fading component calculated from two Gaussian variables [4]. However, these models do not describe the underwater channel accurately because they do not consider several effects such as multipath, fading, shadow zones, which exist in underwater environments.

Considering the received signal as the sum of a large number of multipath arrivals, each of which is modelled as a complex Gaussian stochastic process, the resulting model is the Rayleigh fading channel. Some researchers have modelled the deep water channel as a Rayleigh fading channel, although there is a limited number of available measurements. The shallow water has also been modelled as a Rayleigh fading channel [5] but there is still no consensus among the research community on a model which is applicable for shallow waters [6]. In [7], a simple stochastic channel model is proposed and some experiments are provided for its validation in the shallow water environment in Southampton, United Kingdom. An underwater acoustic channel is introduced in [8] where there can be several propagation paths named eigenpaths over which a signal can propagate from a source to a receiver. Each eigenpath signal contains a dominant stable component and many smaller randomly scattered components named sub-eigenpaths. The number of eigenpaths reaching a receiver has a Poisson distribution and the envelope of the eigenpath signal is described by using a Rice fading model. However, no experimental results are presented in [7].

Moreover, the model does not include acoustic propagation physics, e.g., spreading and absorption.

Recently, a ray-based model is proposed for medium-range very shallow waters in [9] where the signal strength along each ray exhibits independent Rayleigh fading. The model results have been validated through measurements in Singapore. This model includes acoustic propagation physics such as spreading and absorption and captures transmission losses due to sea surface and sea bottom.

However, none of these channel models capture transmission losses due to other different propagation phenomena in the underwater such as surface duct, convergence zones, deep sound channel and reliable acoustic paths as well as the existence and effects of shadow zones.

This paper addresses the observations that have been made in the field of physics and presents a comprehensive overview of the existing underwater channel models. The introduced underwater channels are ray-theory-based models for multipath propagation; the envelope of each ray is modelled as a Rayleigh fading model. We focus on important issues such as multipath and multipath fading and analyze the effects of all existing different propagation phenomena such as surface reflection, surface duct, bottom bounce, convergence zone, deep sound channel, reliable acoustic paths, and other effects such as operating frequency, transmission range, depth, water temperature and the shadow zones. The bit error rates and maximum internode distances are also studied by considering a 16-QAM modulation scheme with OFDM as the multicarrier transmission technique. The research challenges for UWCNs are also pointed out based on our results.

## 3. Underwater signal propagation

### 3.1. Sound propagation in the sea

The study of sound propagation in the sea is fundamental to the understanding of underwater acoustic phenomena and to the development of underwater acoustic applications. Sound propagation in the sea is affected by the physical and chemical properties of the sea water [10].

If a sound source radiates a signal with a source level *SL* decibels at a unit distance (1 yd $=$ 0.9144 m) on its axis, the sound intensity reaching the receiver becomes $SL - TL$. This means that the sound intensity is reduced by the transmission loss *TL* as the sound travels from the source to the receiver. Transmission loss analysis is essential for the study of underwater signal propagation. Therefore in the following sections we carefully analyze *TL* and introduce simple models for the characterization of shallow water and deep water channels.