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Attack Simulation Model and Channel Statistics in Underwater Acoustic Sensor Networks*

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Abstract: In recent years, underwater acoustic wireless sensor networks have been used in many areas. There have been many field trials of acoustic propagation models and statistics for shallow water conditions. However, field trials are limited environmentally and, hence, not widely accepted. Simulations of the impulse response of a shallow underwater acoustic channel allows less expensive system tests that are reproducable. This paper presents a shallow water acoustic channel model based on the actual acoustic propagation characteristics with path attenuation, ambient noise, multiple paths, and Doppler effects. The second-order statistical characteristics of the simulation model are verified with the autocorrelations and crosscorrelations of the quadrature components and the complex envelopes of channel impulse responses. The channel model is implemented in Matlab with the results showing that the absorption coefficient and path losses are both dependent on the frequencies and propagation distances and that the path gain can be improved with Light of Sight (LOS) and short range acoustic propagation. Analysis of the channel impulse response and the frequency response that the zero-order Bessel function of first kind can be used to describe the correlation functions for the impulse response. The shallow underwater acoustic channel is time-varying and can not be modeled as a wide-sense stationary-uncorrelated scattering channel.

Key words: simulation model; absorption coefficient; path loss; Doppler; statistical characteristics

Introduction

Underwater acoustic wireless sensor networks have grown exponentially in many scientific, industrial, and research areas. The network performance is strongly affected by the acoustic propagation characteristics of the underwater acoustic channel. However, underwater acoustic channels differ from radio channels in many aspects, with the underwater channel being a typical dispersive channel characterized by severe multipath effects, strong noise, and long delays. Underwater acoustic channels are recognized as one of the most difficult communication media to analyze[1-3]. The symbol duration decreases with increasing data rate with severe frequency and time variations caused by dispersive fading of the channel. Such effects are more obvious in shallow water environments because the acoustic signals suffer more severe time and frequency selective fading than in radio channels. Therefore, high speed, large capacity, bandwidth-efficient digital communications are different in underwater conditions. Many methods have been developed for this purpose

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such as Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a multicarrier modulation technique which has been widely applied in wireless communication systems and has received considerable attention for underwater acoustic communications over the past two decades[4,5]. The channel state information is necessary for coherent demodulation, inter-carrier interference equalization; carrier frequency offset estimates and others which are key techniques in OFDM systems. Hence, channel simulation models are needed and the channel statistical characteristics need to be analyzed to further improve the performance of high-data-rate underwater acoustic communication systems.

Many field trials have been conducted on acoustic propagation modeling and statistical characteristics under water[6-15]. Surveys have been presented on the propagation characteristics of underwater acoustic signals, such as absorption loss, path loss, noise, multipath, and Doppler effects[6-11]. Nevertheless there is no widely accepted model for acoustic channels because these studies have relied on experimental data collected in localized environments without generalization. Channel statistics are related to probability distributions of channel impulse responses and their statistical properties[12-15]. Rayleigh, Rician, Compound K and Gamma distributions have been used to approximate the probability distributions of the channel impulses[12-14]. However, Rician and Rayleigh distributions are functions of the Rician factor K. If there is no line-of-sight, $K = -\infty$, and the Rician distribution degenerates into the Rayleigh distribution. If $K >> 1$, the Rician distribution approaches the Gauss distribution. Therefore, the probability distributions of the channel impulses in Refs. [12,13] are not unique but depend on the Rician factor K. The Compound K distribution is limited to descriptions of sea clutter and is not suitable for submarine scenarios[14]. The space-time-frequency correlation function[15] was based on the given geometry-based statistical model so it was specifically to model the measured statistical data for the specific underwater acoustic channel. Simulations of radio frequency channels are well established[16,17], but there are limited studies of underwater acoustic channels with few statistical analyses. Multiple independent random processes are difficult to create for a correlated multipath fading channel. The Rayleigh fading model and related models have been widely used to model radio wireless channels, but they are not suitable for underwater acoustic channels because they are deterministic models while underwater acoustic channels are stochastic. There have been many studies to improve the independent statistical properties by designing different quadrature components of the channel impulse responses[16,17] but further analysis of the channel impulse correlation statistics is needed to construct a correct simulation model.

This paper introduces a simulation model for impulse responses of a time-varying shallow water acoustic channel. The simulation model is a superposition of multiple propagation paths whose gains and delays are calculated based on the channel geometry. Each path is undergoing a path loss dependent on the frequency, distance, and incidence angle. Correlation functions are derived for the simulation model, including autocorrelations of the real parts of the impulse responses, autocorrelations of the imaginary parts of the impulse responses, crosscorrelations of the simulated quadrature components of the impulse responses, and autocorrelations of the complex envelopes of the impulse responses. Matlab simulations demonstrate that the channel impulse response, the frequency response, the envelope profiles variation with distance and incidence angle for a given frequency, and the correlation functions compared well with the reference model. Our main contributions are summarized as follows.

(1) A simulation model is given for the impulse responses of a time-varying shallow water acoustic channel characterized by path gain, Doppler effects, multipath effects, and random phases.

(2) The statistics of the impulse response correlation characteristics are analyzed theoretically.

(3) The statistical correlation characteristics are compared with the reference model using Matlab simulations.

1 Propagation Characteristics

Acoustic propagation under water can be represented by the solution of a wave equation based on the boundary conditions for the specific geometry. The solution can be based on ray theory or wave theory. Wave theory is rarely used to model underwater acoustic channels because of the enormous calculations and vague physical images. Because the sound ray image