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A method to estimate the path gains and propagation delays of underwater acoustic channels using the arrival phase information of the multipath components

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ABSTRACT

We propose a method for the estimation of the channel parameters of underwater acoustic channels (UACs) by using a pseudo-noise (PN) sequence. For the channel sounding, the PN sequence is coherently modulated on a carrier frequency by using a binary phase-shift keying (BPSK) modulation scheme. For the demodulation, the arrival phases of the received BPSK signals must be known at the receiver. In practice, however, the arrival phases of the received signal are unknown. We propose to demodulate the received BPSK signal by using an hypothetical arrival phase, which will be increased from 0 to 2π. The demodulated signal obtained by using the hypothetical arrival phase is then correlated with the PN sequence. It is shown that if the hypothetical phase coincides with the arrival phase of a multipath component, then the cross-correlation function (CCF) of the demodulated signal and the transmitted PN sequence reaches its maximum value. Owing to this property, the arrival phases of all channel paths are detected. With the information of the arrival phases of all channel paths, the local maxima of the CCF allow us to estimate the path gains as well as the corresponding propagation delays, which determine the channel impulse response (CIR). To analyse the performance of the proposed channel sounder under real underwater transmission conditions, we have implemented this method to measure shallow UACs in Halong Bay and Hotay lake, Vietnam. Our measurement results show, that the estimated multipath components of the UACs do not significantly vary if the transceivers are moored. In other cases, where the transceivers are moving, the CIR behaves like a fast time-varying process.

1. Introduction

Channel measurements are of outstanding importance for both channel modelling as well as for the design of communication systems. The channel measurement results in terms of the propagation delay profile (PDP), Doppler spectrum, scattering function, and correlation functions provide important information for the development of channel models [1]. Characteristic channel parameters, such as the maximum propagation delay and the maximum Doppler frequency, are essential factors to decide on the bandwidth and the symbol duration of wireless communication systems as well as underwater acoustic communication systems. There are some properties which wireless and underwater acoustic channels (UACs) have in common. They sufer both from multipath propagation and the Doppler effect. Both kinds of channels exhibit fading effects in both time and frequency domain. However, the physical characteristics of the acoustic wave transmission in underwater environments differ greatly from the electromagnetic wave transmission in the air. For example, one of the differences is that the additive noise in radio channels is in most of the cases white and follows the Gaussian distribution. However, the additive noises in UACs are coloured noise, which depends on the carrier frequency and other environmental parameters, such as the temperature, wind speed on the water surface, etc. [2,3]. Moreover, the path loss of the UACs as well as the signal-to-noise ratio (SNR) at the receiver are functions of the transmission distance and the signal frequency [3]. In medium-range communication scenarios and a very shallow water environment, the UAC experiences time-variations and suffers from a high level of non-Gaussian ambient noise [4]. An analysis of the differences between the Doppler effect in the radio channel and the UACs can be found in [5], where the authors show that the Doppler shift and the Doppler spread in the UACs are more severe compared to the case of

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the terrestrial radio frequency channel. This is due to the low acoustic velocity, as well as the variability of the acoustic velocity in underwater transmission environment. Similar to the time-variation effect, the Doppler frequency in the UACs is caused not only by the relative movement of the transmitter and the receiver, but also by the internal currents of the water, as well as by other environment factors [5]. The presence of heavy additive coloured noise, time-variation and Doppler effects, high propagation attenuation, and multipath fading make the UAC sounding task challenging. Difficulties of the radio channel sounding is to obtain the high channel resolution, especially for the broadband channel located in a high carrier frequency. These difficulties lie mainly in the limitation of the hardware performance operating in a high frequency. The UACs usually occupy a carrier frequency and a bandwidth which is lower than that of the radio channels. The hardware performance regarding the precision of the frequency oscillator is not a challenge for the implementation of UAC sounders. The problems are, as mentioned above, the environmental interferences, the time variation effects of the channels, etc. Moreover, the practical working condition of a shallow underwater communication system is even below 0 dB of the SNR [6,7]. Thus, there is a demand to design a channel sounding method providing reliable results in terms of the CIR coefficients and the channel path resolution even under the condition of a very low SNR.

In general, channel sounding techniques can be classified into three categories as follows: impulse method, pseudo-noise (PN) sequence method, and frequency-domain channel measurement method [8–13]. Some studies investigated radio CIR measurements [8,12], whereas other studies focused on measurements of the CIR of acoustic channels [9–11]. The impulse method has been discussed in [8,12], whereby a single impulse or a sequence of impulses is sent out from the transmitter to sound the channel. The transmitted impulse should have a very short duration, such that two adjacent received impulses do not overlap at the receiver. To transmit the sounding signal, a single impulse or a sequence of impulses is modulated on a carrier frequency. In the simplest case, the impulse will directly be transmitted without modulation. The drawback of this straight forward method is its sensitivity to noise [8]. The frequency-domain channel measurement method is discussed in [12,13,18]. The disadvantage of this method is that the procedure is time consuming and not suitable for time-variant channels [12]. The channel sounder method using a PN sequence is described in [8,9,14]. In some studies [11,15], the PN sequence is called the maximum length sequence due to its autocorrelation characteristics. Before sending it out from the transmitter, the PN sequence is usually modulated to a carrier frequency by using an amplitude or a phase modulation method. Similar to the impulse method, the PN sequence can also be transmitted directly over the UAC without using any modulation scheme [16]. However, an unmodulated PN sequence cannot provide good results for the CIR estimation. The coherent binary phase-shift keying (BPSK) modulation scheme is preferred to be used for carrying the PN sequence over radio channels or UACs. The reason is that, for the same transmit power, the BPSK modulation scheme offers a better system performance compared to other schemes. The drawback of this method is that a phase distortion caused by multipath propagation leads to channel measurement errors.

The method proposed in [8] uses a PN sequence modulated by a BPSK scheme for the sounding of wireless channels. The modulated BPSK signal is then added to the carrier frequency component with a phase shift of 90 degrees. Both the sounding signal and the carrier frequency signal are transmitted at the same time. At the receiver, the carrier frequency component is separated from the sounding signal by a band-pass filter (BPF). As the carrier frequency component is transmitted together with the sounding signal, it is obvious that these two signals have the same arrival phase at the receiver. In [8], the authors took advantage of this characteristic to demodulate the received sounding signal. It means, they used the separated carrier frequency component to demodulate the received BPSK signal. The disadvantage of this method is that the carrier frequency component with its delayed phase detected by the BPF will be distorted by noise and multipath propagation. This indicates, that is not able obtain a precise arrival phase to demodulate the received BPSK signal. The key idea of our proposed method is to demodulate the received BPSK signal by using a hypothetical arrival phase, which will be stepwise increased from 0 to 2π. The demodulated signal obtained by the hypothetical arrival phase will then be correlated with the transmitted PN sequence. In case the hypothetical phase coincides with the arrival phase of the received signal from one of the multipaths, the cross-correlation function (CCF) of the demodulated signal and the transmitted PN sequence reaches its maximum value in the phase domain. Based on this property, the arrival phases of all multipath components are estimated. Having the information of the arrival phases of all multipath components, the local maxima of the CCF in the time domain reveals the information of the channel gains, and thus the CIR is detected. Another advantage of our method is to improve the ability to detect the channel path resolution. Almost all of the current conventional channel sounding methods based on the PN sequence have a limited performance when it comes to the channel path resolution [9,14]. It has been shown in [14] that the channel path resolution detected by their method is two times of the bit duration of the PN sequence. We will show in theoretical analysis and in simulation results that our channel sounder provides the minimum channel path resolution, which is the bit duration of the PN sequence.

The rest of this paper is organized as follows. Section 2 describes the proposed method for estimation of the CIR of the UACs. In Section 3, the results of the performance analysis of the proposed method are compared with those of the method described in [8]. Section 4 demonstrates the usefulness of the proposed method by estimating the CIR of real-world UACs, which have been measured in Halong bay and Hotay lake, Vietnam. The conclusion is given in Section 5.

2. A method for the estimation of the PDP of UACs

2.1. The system model

Fig. 1 shows the block diagram of the implemented channel sounder, consisting of a transmitter and a receiver. The task of the transmitter is to send a sounding signal through the UACs via a transducer, which will be received by a hydrophone and processed in the receiver to estimate the channel parameters.

We generate the channel sounding signal by a PN sequence described by a generator polynomial $G(x)$ of degree g. The length of the PN sequence is $K = 2^g - 1$. The PN sequence is a bit sequence, which will be converted into a polar non-return-to-zero (NRZ) sequence $PN(t)$ with a transmission rate of R_b. The transmission rate R_b is chosen in dependence of the bandwidth B of the measured channel, as well as the channel path resolution $\Delta\tau_{\min}$. Thereby, a higher the transmission rate R_b results in a smaller channel path resolution $\Delta\tau_{\min}$, which can be detected. The polar NRZ sequence $PN(t)$ is modulated by means of a BPSK scheme, which results in the sounding signal $s(t)$ according to

$$s(t) = PN(t)\sin(\omega_0 t), \tag{1}$$

where ω_0 is the carrier frequency.

Assuming a stationary transmitter and a stationary receiver, the sounding signal $s(t)$ will be transmitted through a multipath chan-