MEASUREMENT AND MODELING OF FADING IN ULTRASONIC UNDERWATER CHANNELS

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Abstract: *This paper reports measurements for ultrasonic underwater acoustic communication (UAC) channels in Mediterranean shallow waters performed by the company SAES and the research group Ut² of the University of Málaga. Statistical fit to the measured data is also carried out. The measurements have been conducted when the transmitter and the receiver are spaced 50, 100 and 200 m, approximately. Both transducers (B&K 8105 and RESON TC4032) have been placed at depths 3, 6 and 9 m from anchored boats. Faded channel sounding signals have been recorded at frequencies 32, 64 and 128 kHz. After preprocessing the measured data, accurate statistical fit to the recently proposed κ-μ shadowed fading model is obtained; this model includes, among others, the Rayleigh, Ricean and Nakagami-m fading.*

Keywords: *underwater acoustic communications, measurements, fading, κ-μ shadowed statistical model*

1. INTRODUCTION

A crucial aspect for underwater acoustic communication (UAC) is the statistical characterization of the communication channel. High-frequency UAC for short-range applications is very challenging; the promise of small-size transducers has the drawback of fast time-varying channels. Shallow waters UAC channels experience significant fading even when the transmitter and the receiver are not intentionally moving relative to each other. A number of researchers have measured and modeled fading UAC channels in the audio band [1]-[2]; however, fading of ultrasonic UAC channels has been barely investigated. Such channels appear in UAC systems which employs small-size transducers (and consequently with high resonance frequency), e.g. diver-to-diver communications or networks with small-size sensors.

First, measurements for ultrasonic UAC channels are reported in Mediterranean shallow waters, performed by the SAES (www.electronica-submarina.com) and the research group Ut^2 of the University of Málaga (www.ut2.uma.es). Secondly, statistical fit to the measured data is performed. The measurements have been conducted when the transmitter and the received are spaced 50, 100 and 200 m, approximately. Both transducers (B&K 8105 and RESON TC4032) have been placed at depths 3, 6 and 9 m from anchored boats. Faded channel sounding signals have been recorded at frequencies 32, 64 and 128 kHz. After preprocessing the measured data, statistical fit to the recently proposed κ-μ shadowed fading model is performed [3]; this model includes, among others, the Rayleigh, Ricean and Nakagami-*m* fading.

The remainder of this paper is organized as follows. In Section 2 the measurements of ultrasonic UAC channels are described. The statistical fit of the observed fading to the κ-μ shadowed model is presented in Section 3. Finally, some conclusions on our research results are provided in Section 4.

2. MEASUREMENT OF ULTRASONIC UAC FADING CHANNELS

This work is part of a measurement campaign named underwater communication experiments (UCEX). UCEX is a multiyear measurement project of the company Sociedad Anónima de Electrónica Submarina (SAES) and the University of Málaga.

The general scenario considered in this paper is the following: Mediterranean shallow waters (depths from 14 to 30 m), sandy seabed, separations of 50, 100 and 200 m between the transmitter and the receiver; and the projector and the hydrophone suspended from 7 m length anchored boats, both at the same depth (3, 6 or 9 m). Since the main goal of this work is the analysis of the fading statistics, the probe signals employed are sinusoidal of frequencies 32, 64 and 128 kHz. All the measurements in this work were obtained on November 13 (2013) in La Algameca Chica, Cartagena (Spain). The specific data of the different channels considered along this work are provided in Table 1, including a short channel code for future reference.

Channel code	Frequency [kHz]	Transducers' depth [m]	Transducers' separation [m]	Average sea depth [m]	WMO sea state
A6-32	32	6	50	16	2
A6-64	64	6	50	16	2
A6-128	128	6	50	16	2
B6-32	32	6	100	20	2
B6-64	64	6	100	20	2
B6-128	128	6	100	20	2
C3-64	64	3	200	25	2
C9-32	32	9	200	25	2
C9-64	64	9	200	25	2
C9-128	128	9	200	25	2

Table 1: Parameters and conditions of the ultrasonic UAC channels.

The equipment developed for the UCEX measurement campaign uses the projector Bruel&Kjaer 8105 and the hydrophone Reson TC4032, performing accurate noise and channel measurements in the 32-128 kHz ultrasonic band. For each record the sample rate is 1 MHz and the total time duration is 60 s. The records obtained with the UCEX measurement system are digitally post-processed as follows. First, a 400 Hz bandwidth bandpass filter centered at the frequency of the transmitted sinusoidal signal is applied. This bandwidth must be larger than the observed Doppler bandwidth in the experiments and, simultaneously, small enough for cleaning the receiver signal of low frequency and impulsive noise. Then, a simple envelope detector is employed to obtain the normalized channel power gain α^2 (i.e. $E[\alpha^2]=1$), where α represents the channel envelope. The cumulative distribution function (CDF) of the normalized power gain α^2 is defined as

$$F_{\alpha^2}(x) = \Pr\left[\alpha^2 \leq x\right]. \tag{1}$$

Fading of the ultrasonic UAC channels shown in Table 1 is fully characterized by the CDF of the power gain. From Fig. 2 to Fig. 4, the experimental CDFs of the channels given in Table 1 are presented. From the point of view of performance of fading channels it is convenient to represent the CDF of the normalized power gain in a log-log plot; the reason is that the outage probability, average bit-error rate or outage capacity of the channel is primarily determined by the statistics of the fading events. The statistical shape of the measured channels shown in Fig. 2 (distance 50 m) exhibit moderate variations with the frequency; however, channels in Fig. 3 (distance 100 m) are nearly independent of the frequency. Comparing Fig. 2 and Fig. 3 one concludes that the distance between the transmitter and the receiver clearly impact on the shape of the CDF. Fig. 4 presents the measured normalized power gain for the channels with a separation of 200 m between the transmitter and the receiver; it is clearly shown that the depth of both transducers has a great influence on the fading statistics (channel C3-64 versus C9-64).

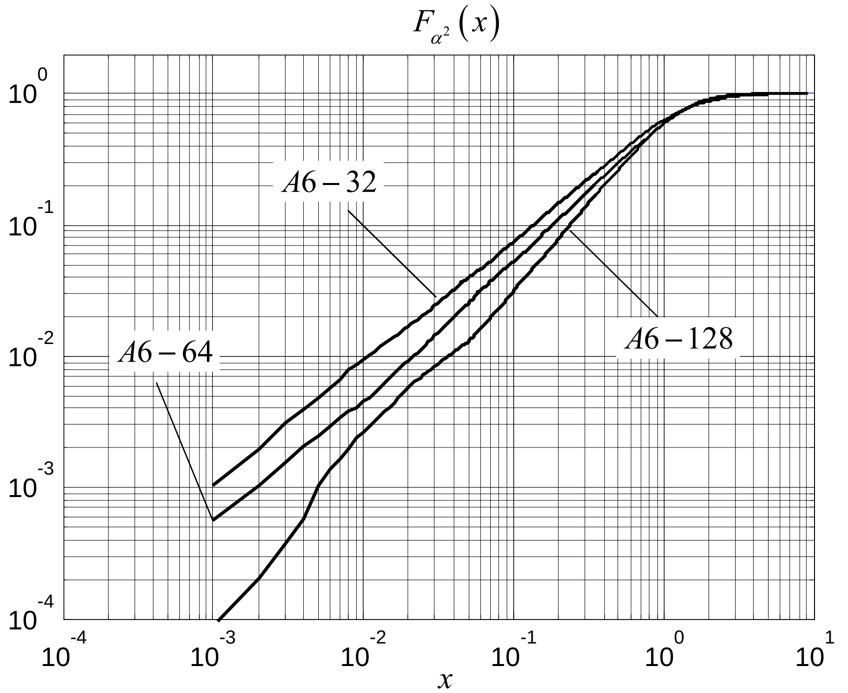

Fig.2: CDFs of the ultrasonic UAC channels A6-32, A6-64 and A6-128.

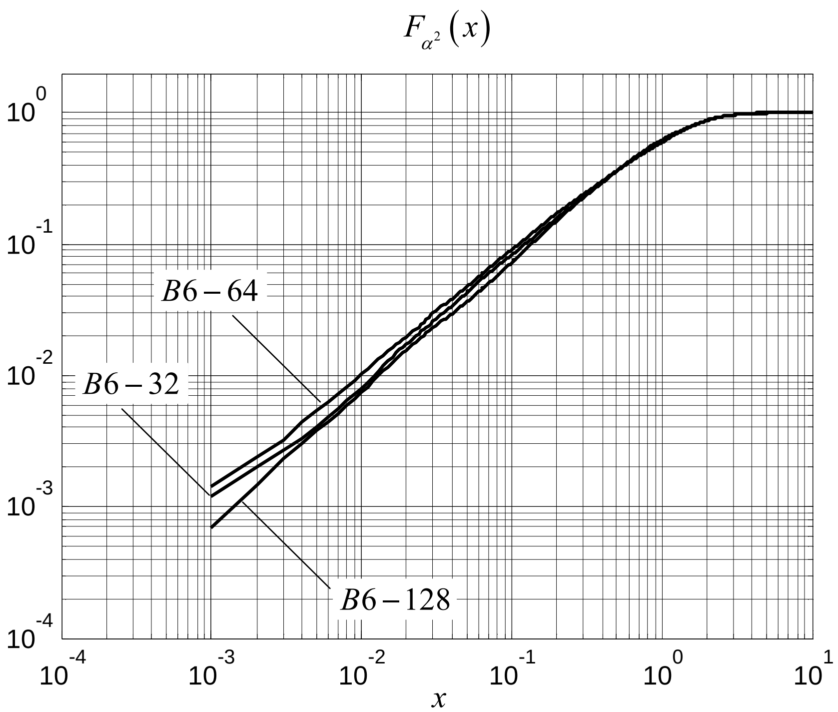

Fig.3: CDFs of the ultrasonic UAC channels B6-32, B6-64 and B6-128.

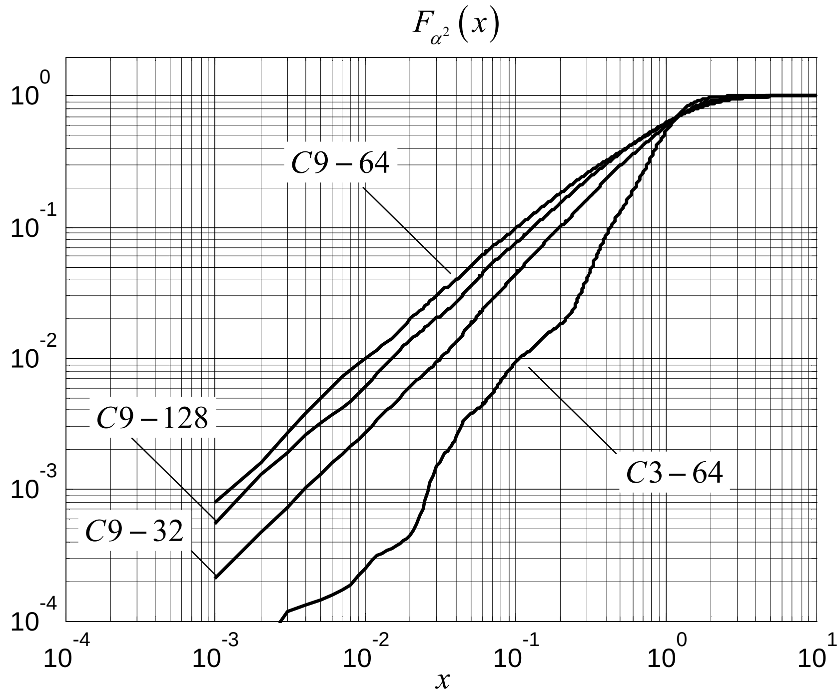

Fig.4: CDFs of the ultrasonic UAC channels C3-64, C9-32, C9-64 and C9-128.

3. MODELING THE ULTRASONIC UAC CHANNELS

The measured ultrasonic UAC channels are modeled in this Section by the κ-μ shadowed fading distribution; this model has recently proposed in [3]. Since the κ-μ shadowed distribution includes the Rayleigh, Rician, Rician shadowed and κ-μ distribution, it provides a very flexible model to fit the experimental data. The CDF of the κ-μ shadowed model for the normalized channel power gain is given by [3]

$$\begin{aligned}\hat{F}_{\alpha^2}\left(x;\kappa,\mu,m\right) &= \frac{\mu^{\mu-1}m^m\left(1+\kappa\right)^{\mu}}{\Gamma\left(\mu\right)\left(\mu\kappa+m\right)^m}x^{\mu} \\ &\times\Phi_2\left(\mu-m,m;\mu+1;-\mu\left(1+\kappa\right)x,-\mu\left(1+\kappa\right)\frac{mx}{\mu\kappa+m}\right),\end{aligned} \tag{2}$$

where μ represents the effective number of clusters, κ is the ratio between the average power of the dominant components and the scattered components, m is the parameter associated to the power fluctuation of the dominant components and Φ_2 the bivariate confluent hypergeometric function [4]. The fit procedure of the CDF in eq. 2 to the experimental data consists on numerically solving the following optimization problem

$$\underset{\kappa,\mu,m}{\text{minimize}}\left(\max_{x}\left|\log_{10}\frac{\hat{F}_{\alpha^2}\left(x;\kappa,\mu,m\right)}{F_{\alpha^2}\left(x\right)}\right|\right). \tag{3}$$

The fit procedure expressed in eq. 3 consists on minimizing the maximum relative deviation between the experimental CDF of the power gain F and the κ-μ shadowed CDF $\hat{F}$ and can be carried out by standard numerical methods. The result of the κ-μ

shadowed modeling is given in Table 2, where the maximum deviation achieved in the fit procedure is indicated.

Channel code	κ	μ	m	$\max_x \left| \log_{10} \frac{\hat{F}_{\alpha^2}(x;\kappa,\mu,m)}{F_{\alpha^2}(x)} \right|$
A6-32	2.33	0.92	1.86	0.029
A6-64	2.90	1.00	3.10	0.068
A6-128	9.56	1.27	1.67	0.114
B6-32	3.03	0.91	2.15	0.056
B6-64	1.89	0.94	1.32	0.049
B6-128	1.99	1.01	1.86	0.022
C3-64	7.71	0.90	18.01	0.205
C9-32	4.06	1.13	2.45	0.026
C9-64	0.03	1.02	6.32	0.053
C9-128	1.56	1.04	2.39	0.040

Table 2: Modeling of ultrasonic UAC channels by the κ-μ shadowed distribution.

4. CONCLUSIONS

This work presents both measurement and modeling of ultrasonic UAC channels performed by SAES (www.electronica-submarina.com) and the research group Ut^2 of the University of Málaga (www.ut2.uma.es). Our main conclusions are that fading in ultrasonic UAC is very significant and that the κ-μ shadowed fading model is quite appropriate for its statistical characterization.

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