Acoustic modem performance assessment via stochastic replay of at sea recorded underwater acoustic communication channels

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ACOUSTIC MODEMS PERFORMANCE ASSESSMENT VIA STOCHASTIC REPLAY OF AT SEA RECORDED UNDERWATER ACOUSTIC COMMUNICATION CHANNELS

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Abstract: *To fully capitalize sea experiments, a channel model driven by real data is presented. This model relies on the assumption that a channel recorded at sea is a single observation of an underlying random process. From this single observation, the channel statistical properties are estimated to then drive a stochastic simulator that generates multiple realizations of the underlying process. Such an approach offers the ability to test underwater communication systems under controlled and reproducible laboratory conditions while guaranteeing a realistic simulation environment. To be as close as possible to the true ocean statistical properties, the often invoked wide-sense stationary uncorrelated scattering (WSSUS) assumption is relaxed. The analyzed channels are shown to be trend stationary and the scatterers are assumed to be potentially correlated.*

Keywords: *Underwater Acoustic Channel, Propagation, Empirical Mode Decomposition.*

1. INTRODUCTION

Accurate underwater acoustic propagation models are essential in order to anticipate the performance of underwater acoustic communication (UAC) systems in the laboratory or to compare new signaling schemes and transmission algorithms to legacy systems. Moreover, unlike other applications of acoustic propagation modeling (such as active or passive sonars), underwater acoustic communications are very sensitive to the fast time variations of the channel response. These fluctuations have therefore to be accurately taken into account which is usually done either by deterministic physic-driven models, by purely stochastic a priori models or by a combination of both (moments of a stochastic model being derived from physical considerations, e.g. [1]).

The proposed paper addresses a new innovative approach, close to the one initially proposed in [2], based upon stochastic replay of previously recorded at sea UAC channels. This approach consists in a two steps procedure. First, using an Empirical Mode Decomposition (EMD) [3], the channel response is split into its (pseudo-)deterministic and random parts. Then, the random part is replayed (another realization of this part is generated, with the same statistical moments as the measured channel response) and added to the (pseudo-)deterministic part. The benefit of this stochastic channel replay is that, thanks to Monte-Carlo simulations, all the metrics used for system design or validation can be computed with a good statistical significance level.

The proposed channel model relies on the analysis of data collected in the Atlantic ocean and the Mediterranean sea. From this set of data, it is shown that we can fully relax the usual (quasi-)wide-sense stationary assumption and also that, thanks to the EMD, a trend stationary model suits the analyzed underwater acoustic communication channels very well. Scatterers with different path delays are also assumed to be potentially correlated so that the true second order statistics of the channel are taken into account by our model.

Test cases finally illustrate the benefits of channel stochastic replay to communication system validation.

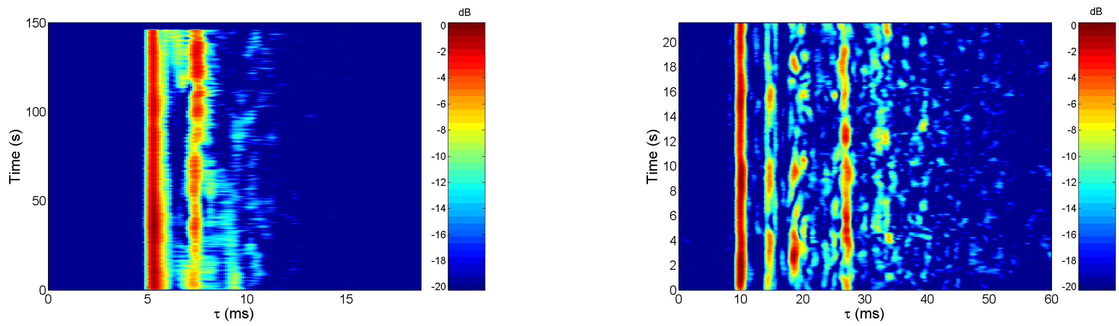
2. SEA EXPERIMENTS

The channel model derived in this paper relies on the analysis of experimental data collected by Thales Underwater Systems in the vicinity of Sanary-sur mer (Mediterranean Sea, France) in October 2004 and by the GESMA (Groupes d’Etudes Sous-Marines de l’Atlantique) in the Brest harbor (Atlantic Ocean, France) in October 2007. The two experimental set-ups, as well as the trial conditions, are summarized in Table I.

For the trials in 2004, a filter matched to a pseudo-random binary sequence was implemented to provide the time evolution of the channel response. In 2007, the experiment was not originally designed for channel sounding so that no dedicated probe signal was used. However, since all the transmitted data were perfectly known at reception, it was possible to provide the channel state information by least mean square data-aided adaptive channel estimation. Figure 1 shows two examples of estimated impulse responses (after compensation of Tx and Rx relative motion).

	Mediterranean Sea (2004)	Atlantic Ocean (2007)
Tx power (dB re 1 μPa @ 1 m)	190	185
Tx-Rx distance range (m)	500-10000	500-3000
Water depth (m)	60-120	10-40
Tx/Rx immersion (m)	20-50	5
Tx/Rx motion speed range (m.s-1)	0-4	0-3
Carrier frequency (kHz)	6	11.2 or 17.5
Probe signal	Pseudo random binary sequence (PRBS) of duration 48 ms repeated every 125 ms as given in [4, pp. 293]. Baud rate: 1kBd	Continuous QPSK modulated data flow at baud rates of 2.9 kBd or 4.35 kBd.
Sea surface conditions	Wind speed 10-15 m/s, moderate waves	Little swell

Table 1: Experimental set-ups



(a) (b)

Figure 1: Examples of measured impulse responses. (a) Atl. Ocean, D=2 km, (b) Med. Sea, D=5 km.

3. STOCHASTIC REPLAY

The stochastic replay relies on the postulate that a communication channel probed at a given location over a given time window is an observation of an underlying random process. Based on this single observation, the objective is then to be able to generate an infinite number of realizations of this process. To build this stochastic generator, the statistical properties of the measured impulse responses have first to be derived.

As detailed in [5], the analysis of the experimental data reveals that each channel tap can be modeled as a trend stationary random process that satisfies

$$g_l(k) = d_l(k) + w_l(k)\,, \tag{1}$$

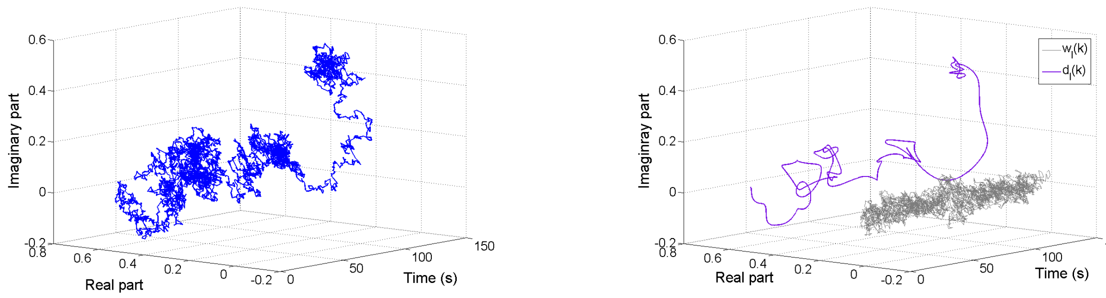
with, for all k, k_1 and $k_2 \in \mathrm{Z}$

$$\mathrm{E}[g_l(k)] = d_l(k)\,, \tag{2}$$

and

$$\mathrm{E}\left[\left(g_l(k_1) - \mathrm{E}[g_l(k_1)]\right)\left(g_l(k_2) - \mathrm{E}[g_l(k_2)]\right)^*\right] = \mathrm{E}\left[w_l(k) w_l^*(k + k_2 - k_1)\right]. \tag{3}$$

$g_l(k)$ is the output of the channel estimation representing the k-th sample of the l-th tap. $d_l(k)$ is called the *trend* which is a pseudo-coherent component that behaves almost as if the medium was deterministic and $w_l(k)$ is a zero-mean wide sense stationnary ergodic random process. $d_l(k)$ can be seen as the contributor to slow fading whereas $w_l(k)$ represents the channel fluctuations attributable to the scatterers that result in fast fading. In order to isolate $d_l(k)$ and $w_l(k)$ from $g_l(k)$, an empirical mode decomposition (EMD) is performed on each tap. EMD is a method of signal decomposition, well suited to non wide-sense stationary signals, that does not require any predetermined basis functions. The decomposition is designed to seek the different intrinsic modes of oscillations (or rotations in the complex case) in any data, based on the principle of local scale separation [3]. The detail of the decomposition procedure is given in [5]. Figure 2 shows the EMD filtering applied to the tap at $\tau = 7$ ms of the channel displayed in Figure 1-(a).



(a) (b)

Figure 2: Illustration of EMD filtering applied to a real channel tap. (a) Original tap, (b) Separation of the trend and the random component.

In our approach and at our observation scale, $d_l(k)$ is considered to be deterministic so that the randomness of each channel tap is expressed by $w_l(k)$. Consequently, the observation vector $[w_0(k), \cdots, w_{L-1}(k)]$, where L is the number of channel taps, is considered as a single realization of a multivariate random process. Our objective is now to generate new realizations of this process while being as close as possible to the true underlying process. Statistical analyzes show that $w_l(k)$ is zero-mean Gaussian distributed. However, no general parametric model for its second order statistics, represented by its Doppler power spectrum, has been found. Nevertheless, providing that the observation duration is greater than the channel coherence time, it is shown in [5] that the second order statistics can be very well approximated by slightly modifying the Rice method for generating Gaussian processes [6]. Scatterers with different path delays are assumed to be potentially correlated so that the true second order statistics of the channel are taken into account by our model. Reflections on a same physical body or delay/Doppler leakage caused by band- or time-limited transmitted data can indeed induce correlations between multipath components. The overall procedure for generating new realizations of the observed channels is summarized by the pseudo-code given in Algorithm 1.

Algorithm 1 Channel stochastic replay

Require: A probed channel of L taps over an observation windows of N samples (TX/RX motion must be compensated).

1. Draw N realizations $\theta(n)$ of a uniformly distributed random variable in $(0,2\pi]$

for $0 \le l \le L-1$ **do**

2. Using the EMD, decompose each tap $g_l(k)$ as $g_l(k) = d_l(k) + w_l(k)$

3. Compute $W_l(n) = \frac{1}{\sqrt{n}} \sum_{k=0}^{N-1} w_l(k) e^{-2i\pi nk/N}$

4. Compute $\lambda_l(k) = \frac{1}{\sqrt{n}} \sum_{n=0}^{N-1} W_l(n) e^{2i\pi nk/N} e^{i\theta(n)}$

5. Add $\lambda_l(k)$ to $d_l(k)$ to get a new realization of the channel tap l

end for

The Matlab code corresponding to the proposed simulator is available at http://perso.telecom-bretagne.eu/fxsocheleau/software.

4. ILLUSTRATIONS

The channel replay approach can prove to be a good complementary test method to field trials. While field trials guarantee realistic testing conditions, they are limited to a narrow validation scope since they correspond to “snapshots” of specific operational environments. Channel replay is of great interest to fully exploit sea experiments under controlled and reproducible laboratory conditions. For instance, it can be used to:

- compute fading statistics useful to design error-correcting codes,
- compare competing transmitter/receiver techniques(multi-carrier vs single carrier, equalizer structures, synchronization algorithms etc.),
- assess the channel capacity (see [7]),
- independently assess the contributions of different physical phenomena.

The benefit of the stochastic characteristic in the channel replay is that, thanks to Monte-Carlo simulations, all the metrics used for system design or validation can be computed with a good statistical significance level.

To illustrate the relevance of channel replay for system validation, we hereafter consider two simple case studies. The first case corresponds to a situation where a system designer would like to estimate the SNR increase required to improve the spectral efficiency of its system. As shown in Figure 3 for instance, this can be done by measuring the bit-error rate (BER) as a function of Eb/N0 for various system configurations. As the objective here is not to test a particular system but to exhibit some possibilities offered by the channel replay, we have considered for the simulation an ideal single-carrier system perfectly symbol synchronized with an adaptive data-aided intersymbol interference canceler. No error-correcting codes are used. By testing various configurations in various environments, the system designer may identify guidelines useful to choose the right throughput/robustness compromise.

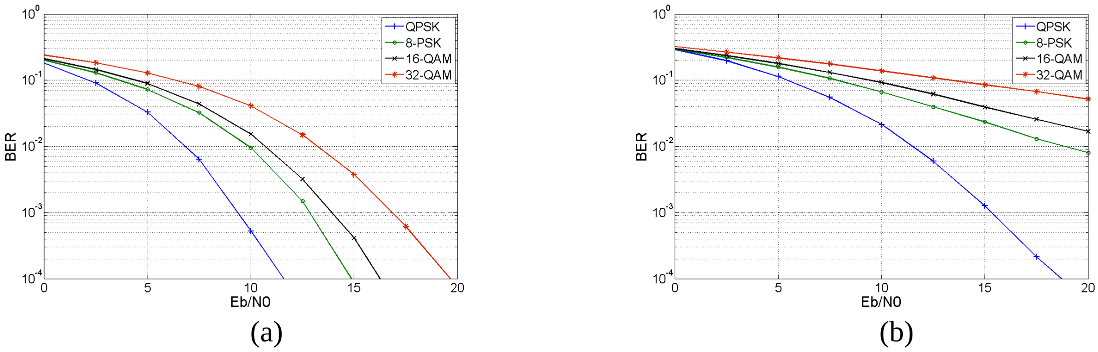


Figure 3: Bit error rate vs Eb/N0 for various modulation orders. (a) Atlantic channel shown in Figure 1-(a), Mediterranean channel shown in Figure 1-(b).

Channel replay may also be useful to tune the receiver algorithms. For instance, it may be interesting to know to what extent the receiver is able to track the fast fluctuations of the channel. This can be done by estimating the bit-error rate (BER) as a function of Eb/N0 for various power ratios *K* between the pseudo-deterministic and the random components of the channel. Since we are able to isolate both components, we can artificially change the power of one or the other and measure the impact of this change on the BER. This is illustrated in Figure 4 for the Atlantic channel shown in Figure 1-(a) where *K* is artificially reduced to 0 dB by step of 3 dB, the true power ratio *K* being 18 dB.

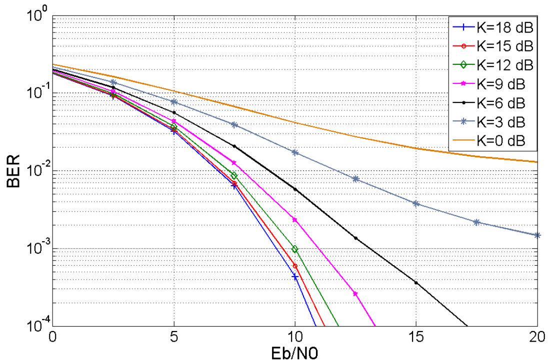


Figure 4: Influence on the BER of the Atlantic channel of the power ratio between the pseudo-deterministic and the random components.

Note that other illustrations of channel replay are shown in [5].

5. CONCLUSIONS

In the absence of standardized channel model, stochastic channel replay can be very useful to design and validate underwater communication systems. Such a simulation approach can also be relevant to compare competing transmission systems or to compute capacity bounds. The proposed model takes into account the non wide-sense stationary nature of the analyzed channel and also integrates the potential correlation between taps. The main limitation of the method discussed in this paper holds in that the channel replay cannot be extended beyond the duration of the original estimated impulse response. Such an extension would require to characterize and model the slow channel fluctuations.

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