TRANSMISSION PARAMETERS OF UNDERWATER COMMUNICATION CHANNELS[1]

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The underwater environment is tough and demanding as a communication channel for ultrasonic signals. The channel transmission characteristics in marine and inland waters depend much on local bathymetry and changing weather conditions. The architecture and performance of a reliable underwater acoustic communication (UAC) system should allow real-time adaptation of its transmission parameters to a large variety of possible channel characteristics. The paper presents an adaptation procedure based on the WSS-US statistical model developed for wireless telecommunication systems. The channel is there characterized by measurements of instantaneous channel impulse response being then a basis for estimation of the channel statistical characteristics and extraction of related parameters in the phase of communication handshake, and next used in the adaptive design of digital communication system transmission settings recorded at the physical and link layers of the communication protocol

INTRODUCTION

Underwater acoustic communication (UAC) systems, although working in much different physical environment than wireless systems, have been making use of recent dynamic developments of radiocommunications standards and techniques.

Transmission performances of shallow underwater acoustic (SUWA) channels are strongly limited due to multiple reflections from irregular bottom and moving water surface, that leads to signal multipath, nonstationarity and other distortions. At the reception, the communication signal suffers from intersymbol interferences (ISI) and frequency dispersion caused by the Doppler effect – much more pronounced in ultrasonic signals than in the case of electromagnetic ones. When a multicarrier signal is transmitted, the frequency dispersion can lead to intercarrier interferences (ICI) clearly observed in signal spectrum.

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In wireless communications, the deviation of the attenuation that a carrier-modulated telecommunication signal experiences due to multipath propagation, is known as radio signal fading. The phenomenon is modeled with statistical tools of analysis. Channel statistics are based on measurements of impulse responses from which statistical characteristics of the first and the second order are analyzed. A set of basic transmission parameters of the channel is calculated, which implies, in turn, a choice of desired properties of communication signalling.

In a practical system, the SUWA channel instantaneous performances are not known and have to be estimated. Hence the channel transmission properties are measured during the so-called handshake phase of transmission protocol, similarly to procedures of wireless electromagnetic systems. The handshake is a procedure at the beginning of a communication, initiating the connection between two correspondents. The measurement of the channel impulse response is an integral part of the handshake sequence. The frequency at which the estimates need to be updated depends on the channel dynamics, be it with 'slow' or 'not-so-slow' variations.

1. SHALLOW WATER ACOUSTIC COMMUNICATION

Depending on the site of action of an underwater acoustic communication (UAC) system, there are two basic mechanisms of multiple paths of propagation related to a SUWA channel: (1) reflections from medium boundaries (bottom, water surface and objects in the water), and (2) refraction as a result of non-uniform vertical distribution of sound propagation velocity. In the 'reflection' channel the multipath propagation has a discrete character and the impulse response is quasi-discrete and sparse. Multipath propagation in the 'refraction' channel, in turn, manifests itself in the continuous character of the impulse response.

A signal arriving at an UAC system receiver, consists of many delayed and attenuated replicas of the transmitted waveform. Compared with the transmitted signal, it is considerably spread in time. There is a strong time dispersion observed in the impulse response of a channel with multipath propagation. It causes intersymbol interferences in the received signal, that are observed as frequency selective fading.

Due to the time-variability of a multipath channel, each received signal path induces some random amplitude, phase, and Doppler shift fluctuations. In a typical multipath environment, the received signal is composed of several reflected paths with different path distances and angles of arrival, and the Doppler shift of each arriving path, induced by water surface local movements, is generally different from that of another one. The effect on the received signal is seen as a Doppler spreading of the communication signal spectrum [1–2]. In multicarrier communication systems, strong Doppler spread manifests itself as a fast fading of the received signal in the time domain, or intercarrier interferences in the frequency domain, that significantly reduces the communication performance of the system [3].

Measuring and analyzing a channel's parameters is a necessary step for the design of a successful communication system [4]. Implementation of correctly adopted modulation and coding techniques developed as current standards of wireless telecommunications, to the properties of underwater channels, should significantly improve the quality of underwater acoustic communication. The solutions are searched for the adaptive optimization of the transmitted signal parameters in response to communication channel conditions, for maximizing range, speed and reliability of data transmission in marine and inland waters.

The most favorable communication condition exists when the range is short compared to the water depth. The corresponding deep underwater acoustic (DUWA) channel can be treated as a stable, deterministic one, with no need for statistical modelling. The UAC system delivers then its whole predisposed data rate. Only the frequency and range-dependent attenuation should be taken into account.

In any case, the knowledge of channel features is a foundation of a reliable UAC system design and operation.

2. TRANSMISSION CHANNEL MODELING

There is no typical underwater channel. Each specific environment possesses different characteristics that affect the potential performance of digital communication systems. The adaptation of modern data transmission techniques to ultrasound underwater communication requires assumption of a flexible channel model, which takes into account the diversity of the phenomena occurring in it.

Design ‘on the fly’ is needed that would follow changes, whether slow or quick. The orthogonal frequency division multiplex (OFDM) scheme is in practice the most promising. Due to the complexity of acoustic wave propagation mechanism, it is practically impossible to construct a deterministic model for an underwater communication channel. The number of cases determined by the position of potentially moving transmitter and receiver, bathymetric terrain configuration, possible obstructions, moving water surface causing the reflection and diffraction is practically unlimited. A statistical approach in this case turns out to be the only option; hence a need to treat the channel impulse response as a stochastic process. Furthermore, the model should be universal. It can not refer to one specific example of the channel, but has to reflect statistically the situations that may occur during signal transmission from the transmitter to the receiver.

The model is adopted where variations of signals arriving with different delays are treated as uncorrelated, and correlation properties of the channel – as stationary. In other words, the so-called WSS-US assumption is made, meaning that the channel is stationary in a wide-sense (Wide-Sense Stationary), and that the multipath scattering is uncorrelated (Uncorrelated Scattering). In wireless telecommunication, the statistical description of a communication channel is simplified. It turns out, however, to be an appropriate assumption for most of radio channels [3, 5, 11]. Real UAC channels are hardly ever WSS-US, as illustrated in [6]. However, the rationale of the WSS-US modeling is that over a restricted period of time this assumption is reasonably satisfied [7].

The WSS-US model allows for simultaneous modeling of time dispersion (leading to the frequency selectivity of the channel) and time variability (resulting in frequency dispersion). Functions of the WSS-US model are defined in time and frequency domain using four variables: relative time between impulse response measurements Δt, relative frequency component of signal spectrum Δf, time delay τ of multipath components of impulse response and Doppler frequency shift ν. The variables are, pair by pair, dual domains of Fourier transformations (Table 1).

Table 1. Domains of WSS-US functions

variable	symbol	relation
difference between moments of impulse response measurements	$\Delta t = t_1 - t_2$	$\Delta t \xleftrightarrow{F} \nu$
difference between spectral components of impulse response	$\Delta f = f_1 - f_2$	$\Delta f \xleftrightarrow{F} \tau$
time delay	τ	$\tau \xleftrightarrow{F} \Delta f$
Doppler shift	ν	$\nu \xleftrightarrow{F} \Delta t$

It is assumed that nonstationary channel impulse response (Fig. 1), represented by the complex Gaussian process $h(\tau;t)$, is a zero-mean function for all t and τ. It is wide-sense stationary (WSS) in t, that refers to the channel time-variability, and has uncorrelated scattering in τ (US), that refers to the multipath propagation of the transmitted signal.

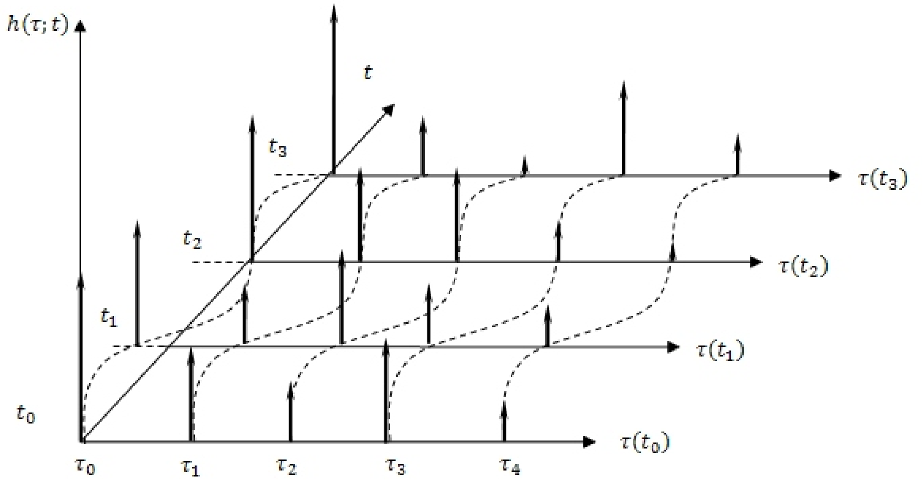

Fig. 1. An example of time-varying discrete-time impulse response

Under the WSS-US assumption, the correlation function between two multipath components of delay τ_1 and τ_2 of impulse responses observed in two different moments t_1 and t_2 can be written as:

$$\phi_{hh}(\tau_1,\tau_2;t_1,t_2) = E\{h^*(\tau_1,t_1)h(\tau_2,t_2)\} = \phi_{hh}(\tau_1;\Delta t)\delta(\tau_1-\tau_2) \quad (1)$$

The correlation function $\phi_{hh}(\tau_1;\Delta t)$ has a nonzero value only when the delays τ_1 and τ_2 are equal. In addition, the value of the correlation function depends only on the difference of impulse response observation times Δt, rather than the absolute time t.

3. WSS-US CHANNEL MODEL FUNCTIONS AND PARAMETERS

The *scattering function* is defined as the Fourier transform of correlation function $\phi_{hh}(\tau_1;\Delta t)$, with respect to the Δt parameter:

$$S(\tau;\nu) = \int_{-\infty}^{\infty} \phi_{hh}(\tau;\Delta t)e^{-j2\pi\nu\Delta t}d\Delta t \quad (2)$$

The scattering function gives the average power output of the channel as a function of time delay τ and Doppler frequency ν, and is the basis for computing the remainder of the WSS-US channel characterization functions (Table 2). Fig. 2 shows the relationship among WSS-US channel functions and parameters.

Time dispersion of the channel is characterized by the *multipath intensity profile* $\phi_h(\tau)$, which gives the average power output as a function of time delay τ. For a single transmitted impulse, the time τ_{max} between the first and last received component represents the *maximum excess delay*, during which the multipath signal power falls to some threshold level (10 or 20 dB) below that of the strongest component. A more useful measurement of delay spread for communications systems designers is the root mean squared delay τ_{rms}, which is the second central moment of $\phi_h(\tau)$ [3].

Table 2. Selected functions of WSS-US model

function	domain	type of function	relationship	associated parameter
multipath intensity profile $\phi_h(\tau)$	τ	average power distribution	$\phi_h(\tau)=\int S(\tau;\nu)d\nu$	delay spread τ_{rms}
spaced-frequency correlation function $\phi_H(\Delta f)$	Δf	correlation function	$\phi_H(\Delta f)=\int \phi_h(\tau)e^{-j2\pi\Delta f\tau}d\tau$	coherence bandwidth Δf_c
Doppler power spectrum $S_H(\nu)$	ν	power density function	$S_H(\nu)=\int S(\tau;\nu)d\tau$	Doppler spread f_m
spaced-time correlation function $\phi_H(\Delta t)$	Δt	correlation function	$\phi_H(\Delta t)=\int S_H(\nu)e^{-j2\pi\Delta t\nu}d\nu$	coherence time Δt_c

The excess delay spread τ_{rms} (or $\tau_{\max}$) of the channel places a limit on the duration of a transmission symbol T_s. If $\tau_{rms} > T_s$, the channel exhibits frequency selective fading, which results in channel-induced ISI, and the communication system needs to perform equalization to mitigate the distortion. If $T_s > \tau_{rms}$, the channel exhibits flat fading, that does not result in ISI.

Spaced-frequency correlation function $\phi_H(\Delta f)$ describes the frequency variability corresponding to the time dispersion of the channel. It provides a measure of the frequency coherence of the channel. This function indicates the *coherence bandwidth* Δf_c, which is a statistical measure of the range of frequencies over which the channel passes all spectral components with approximately equal gain and linear phase. The coherence bandwidth and rms excess delay are reciprocally related as follows:

$$\Delta f_c \approx \frac{1}{a\tau_{rms}} \tag{3}$$

If the coherence bandwidth is defined as the bandwidth over which the spaced-frequency correlation function is above 0.9, then $a = 50$. If the definition is relaxed so that the frequency correlation function is above 0.5, $a = 5$ [3].

The coherence bandwidth Δf_c sets an upper limit on the communication system signaling rate W which can be used without suffering frequency-selective distortion. The signal bandwidth W should be less than the coherence bandwidth Δf_c:

$$\Delta f_c > W \approx \frac{1}{T_s} \tag{4}$$

In such a case the channel affects all the frequency components in a similar manner (Fig. 3).

Doppler power spectrum $S_H(\nu)$ describes frequency dispersion of the channel, providing the signal intensity as a function of the Doppler shift ν. The range of frequencies over which the Doppler power spectrum is essentially nonzero is known as the *Doppler spread* f_m.

The Doppler spread f_m (which refers to the channel fading rate), sets a lower limit on the communication system signaling rate W, that can be used without suffering fast fading distortion. The bandwidth W should be much greater than Doppler spread f_m (Fig. 3):

$$W >> f_m \tag{5}$$

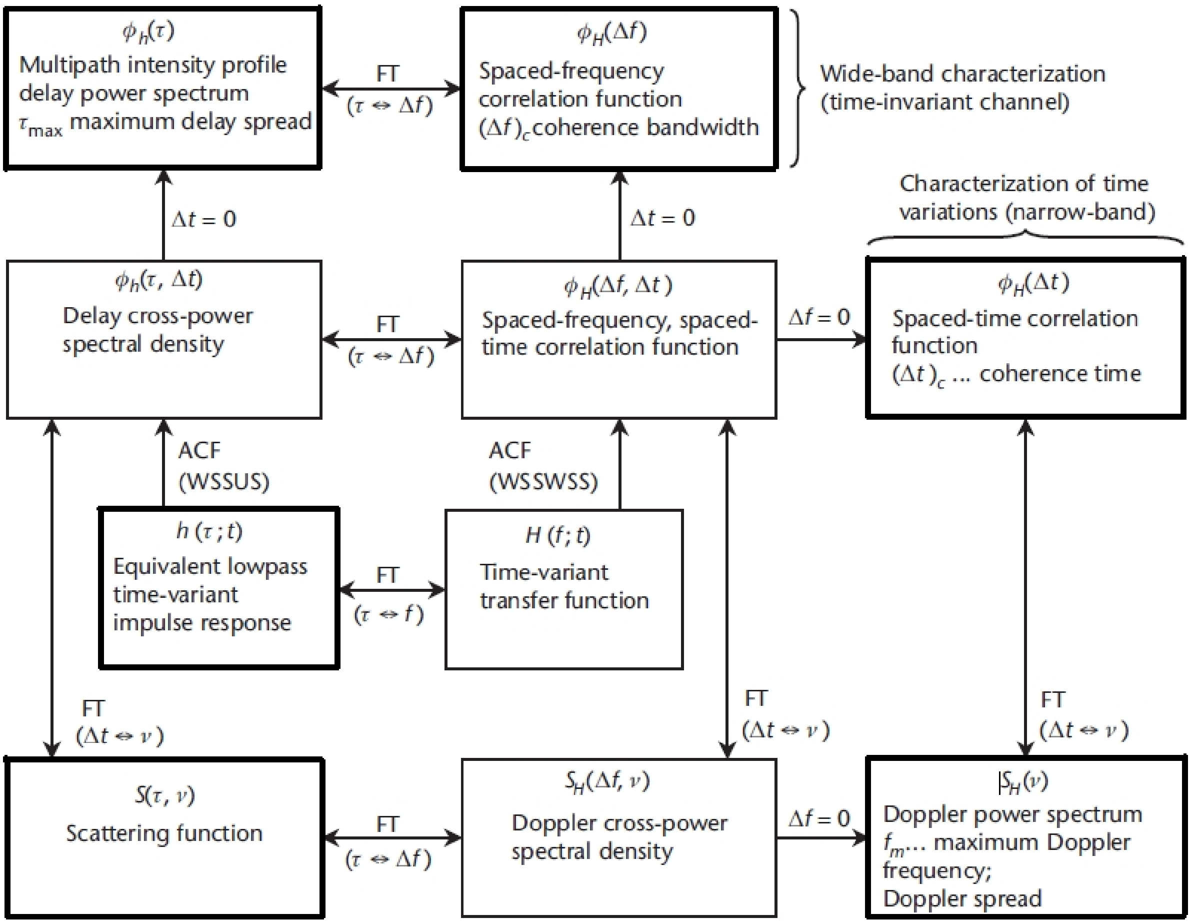

Fig. 2. Relationship among WSS-US channel correlation functions and power density functions [11]

Spaced-time correlation function $\phi_H(\Delta t)$ describes the time variability corresponding to the frequency dispersion of the channel. It is the autocorrelation function of the channel's response to a sinusoid. This function specifies the extent to which there is correlation between the channel's response to a sinusoid sent at time t_1 and the response to a similar sinusoid sent at time t_2, where $\Delta t = t_1 - t_2$. The *coherence time*, Δt_c, is a measure of the expected time duration over which the channel response is essentially invariant. The Doppler spread, f_m, and the coherence time, Δt_c, are reciprocally related. When Δt_c is defined more precisely as the time duration over which the channel's response to a sinusoid has a correlation greater than 0.5, the relationship between Δt_c and f_m is defined as [3]:

$$\Delta t_c = \sqrt{\frac{9}{16\pi f_m^2}} \approx \frac{0.4}{f_m} \tag{6}$$

The spaced-time correlation function yields the time-variance of the channel in terms of the coherence time Δt_c. If $T_s > \Delta t_c$, fast fading degradation occurs, since the channel's conditions change within the duration of a single symbol. As long as the symbol time T_s is much shorter than Δt_c, the channel is considered to be a slow fading one.

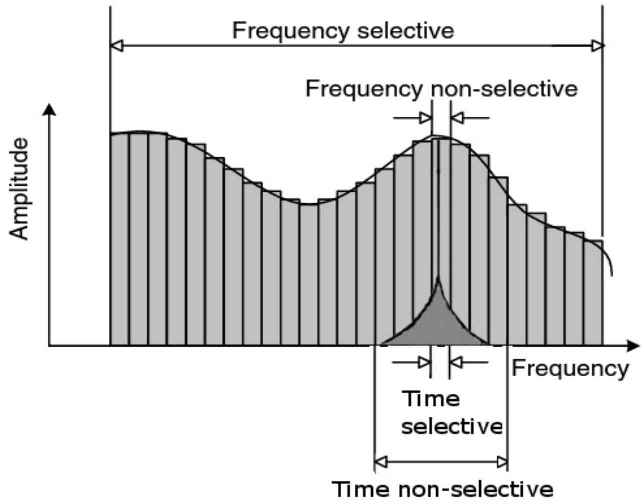

Fig. 3. Frequency- and time-selective, and non-selective channel characteristics, as related to the spectrum of communication signal and its Doppler spread

4. INITIATION OF UAC TRANSMISSION

For communication needs, a WSS-US channel is fully described by the impulse response, frequency characteristics and first- and second-order statistics: correlation functions and power distributions in time and frequency domain. There are several parameters related to the statistical characteristics: delay spread and Doppler-shift spread, coherence bandwidth and coherence time, which are crucial for the process of the design of the physical layer transmission protocol. Depending on the values of statistical parameters calculated from the impulse response measurements, the instantaneous properties of the transmitted signal can be set during the handshake (Fig. 4).

It is necessary to describe the underwater channel in terms of telecommunication channel with a specific, time-variant impulse response $h(\tau;t)$, where t is a running time indicating subsequent transmission moments and τ is a small-scale communication time counted from the start of each transmission. In order to produce the channel's statistical characteristics with enough resolution, the channel needs to be sounded as often as necessary.

The excitation signal and the deconvolution technique used for the channel impulse response measurements, have to maximize the signal-to-noise ratio of the deconvolved impulse response [8]. The signal should have autocorrelation function as similar to the Dirac delta impulse as possible. Moreover, it should be resistant to various kinds of noise. These requirements determine the choice of the correlation measurement method that uses pseudo-random binary signals, such as maximum length sequences (MLS), otherwise broadly used in spread spectrum communications, radar pulse compression technique and architectural acoustics [9, 10].

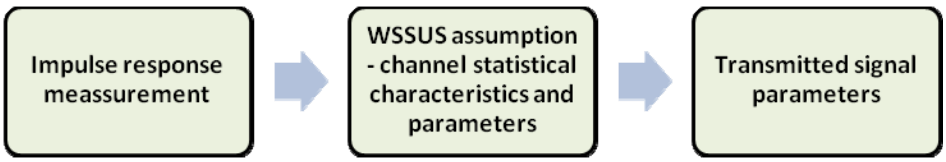

Fig. 4. Schematic diagram of transmission protocol handshake

A handshake including the channel impulse response measurement should be repeated whenever there is an excessive rate of uncorrectable errors and there is a reason to believe that this has been caused by an excessive change of the transmission channel characteristics, exceeding the standard tolerance of the model.

5. CONCLUSIONS

Nonstationary interference, multipath propagation and a strong influence of the Doppler effect require the use, in UAC systems, of modulation and coding techniques having an adaptation range considerably beyond that found in current wireless telecommunications. The wide sense stationary uncorrelated scattering (WSS-US) assumption significantly simplifies calculations. Statistical characteristics of the channel are there estimated on the base of time-varying impulse response measurements performed during the handshake phase of transmission protocol.

The method for adaptive matching of transmitted signal parameters to instantaneous underwater channel characteristics is being implemented in a laboratory model of wideband UAC system using OFDM modulation and coding technique. The research is being performed in the Department of Marine Electronic Systems in Gdańsk University of Technology, and is supported by a grant from the Polish Ministry of Science and Higher Education.

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