Ultrasonic Link for Improved Incoherent Data Transmission in Horizontal Shallow Water Channels

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***Abstract*- An acoustic telemetry link may be disturbed or even collapse due to non-stable intersymbol interferences resulting from the effect that transmitted signal takes numerous, time-varying different-length paths to receiver. The complex time variations of multipath arrivals create an extremely hard problem for equalizers used for processing of conventional frequency-constant carrier signals. Our studies on underwater communication of dolphins revealed several solutions to overcome these problems. It turned out that chirping and singing is most essential in this conjunction. Applied to technical telemetry, underwater communication could be substantially improved by the implementation of the method called Sweep-Spread Carrier Communication. In this method, carrier signal consists of a succession of sweeps, which cause permanent rapid fluctuation of signal frequency. When converting received signal into constant intermediate frequencies, multipath arrivals can be resolved and separated not as traditionally in time domains, applying complex equalizers, but – much easier - in frequency domains by means of usual band-pass filters. As the experimental results show, this kind of signal processing improves statistical channel properties, providing increased data rates and high transmission stability, which were confirmed in validation experiments recently carried out in shallow fresh and sea water channels.**

I. Introduction

Underwater acoustic telemetry channels are frequency limited and distinguished with high reverberation levels complicating development of systems that could provide high bit rates and robustness of data exchange.

In underwater telemetry systems of two types are used - phase coherent and incoherent. The last ones are characterized with high robustness and the first ones - with high bit rates. Incoherent methods are used more frequently in commercial communication applications. Phase coherent systems often remain in form of prototypes developed in numerous academic research programs. Incoherent systems have advanced market chances if an industrial application under real conditions is required.

Deficiencies of contemporary methods are inefficient frequency use, especially noticeable under conditions of strictly limited frequency bandwidth, and also inability of incoherent methods to compensate for reverberation effects, which often appears in channels of practical interest. These shortages put obstacles for achieving required bit rates. Statistical channel characteristics, like bandwidth and channel coherence time, vary rapidly in time, and even hypothetical systems, that would adjust their parameters during an actual session, could not exploit a given channel in optimal way. Frequent parameter readjustments and retransmission of (overhead-) service signals between transmitter and receiver would lead to considerable reduction of an effective bit rate.

In the next sections a technique is presented, which allows an essential improvement of bit rates achievable by use of incoherent communication systems keeping inviolable their valuable feature – robustness. Theoretical basis and experimental results are given for evaluation of the technique.

II. Physical Peculiarities of Underwater Telemetry Channel

Performance of an acoustic telemetry system is usually almost not restricted by high levels of white additive noise. Dominating interest consist in solution of problems connected to strong bandwidth restrictions because of absorption of high frequencies in sea water, and especially problems produced with high reverberation levels of two types: 1) spread of receive signal in time domain (multipath reverberation) and 2) spread of receive signal in frequency domain (Doppler reverberation).

Time spread of a receive signal is dictated by presence of many signal propagation paths of different length. Due to multipath propagation intersymbol interference in underwater channels can often achieve tens or even hundreds of symbol lengths.

Nonstationary transmitting channel behavior is caused with wave movements (internal and surface waves) and transmitter/receiver movements, which are often subdivided into an average Doppler shift and a random dispersion about the average. An impulse response of such a channel appears to be a very complex time and frequency dependency.

The influence of such channel behavior is reflected particularly by a small scale fading providing significant amplitude and phase fluctuations of a receive signal. In shallow water telemetry the small scale fading has usually Rayleigh nature, where the receive signal consists of many multiple reflections and do not have a dominant (direct) arrival. An exception represents short distance channels usually distributed according to Rice probability function [1].

Extended time spreads specify correspondingly low bit rates. A coherence bandwidth can vary in a wide range of values. An excess time delay in shallow water channels remains in the range between some milliseconds and some tens of milliseconds providing a range of coherence bandwidth values between several tens of hertz and several

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kilohertz. Coherence bandwidth of deep water channels achieve even bigger values, i.e. ranges from several hertz to several tens of kilohertz. In the last case it depends on the ratio between communication distance and transmitter/receiver depth. By small ratios the time spread has short durations, especially when surface and ground reflections are absent in structure of a receive signal. A presence of powerful multipath arrivals and correspondingly large values of time spreads are typical for greater distance/depth ratios. Extended time spreads can be also often observed when transmitting/receiving devices are placed near to sound axis, where coherence bandwidth can often comprise a value of only several hertz.

It is well known, that a coherence bandwidth corresponds to reciprocal of a time spread within an accuracy of a constant factor. Therefore, if one could influence an excess delay spread, a coherence bandwidth would correspondingly become a controllable value. For example, a coherence bandwidth would increase with decreasing a multipath spread duration of a receive signal. In the next section a technique is described, where a spread spectrum signal is transmitted over a multipath channel and processed afterwards by means of an algorithm that provides a filtering of received multipath components using traditional pass-band filters, thus improving statistical characteristics of received signals (i.e. coherence bandwidth and coherence time).

III. Signal Propagation in Time Dispersive Channels

A. Stationary transmission

In complex form a transmitting signal can be described as follows [2]:

$$s(t) = \mathrm{Re}\{g(t)\exp(2\pi i f_c t)\}, \qquad (1)$$

where *Re{·}* is a real part of the expression in curly braces, f_c is a carrier frequency, *g(t)* represents a narrow-band signal containing an information to transmit and is known as a complex envelope of the transmitting signal *s(t)*.

After time spread in a channel characterized by many propagation paths, a receive signal consist of a sum of delayed multipath components with variable excess propagation delays $\tau_n(t)$ and variable amplitude factors $\alpha_n(t)$.

Neglecting the noise, the receive signal may be described as in [2]:

$$r(t) = \sum_n \alpha_n(t) s\{t - \tau_n(t)\}, \qquad (2)$$

and after substitution (1) into (2) it takes the form:

$$z(t) = \sum_n \alpha_n(t)\exp(-2\pi i f_c \tau_n(t)) g\{t - \tau_n(t)\}. \qquad (3)$$

While transmitting an unmodulated carrier (i.e. $g(t) \equiv 1$), the receiving signal simplifies to:

$$z(t) = \sum_n \alpha_n(t)\exp(-2\pi i f_c \tau_n(t)). \qquad (4)$$

Owing to nearly linear nature of acoustic signal propagation in water, a frequency value of a transmit signal remains constant. However, amplitude and phase values will depend on random properties of a propagation medium. Therefore, multiptah components, arriving over a multiplicity of propagation paths, where each one has the same frequency but random amplitudes and phases, will interfere and create a resulting signal characterized with random parameter fluctuations.

Furthermore, contemporary requirements of high bit rates determine a relationship between a symbol duration T_s and a time spread T_m as follows: $T_s < T_m$. This inequality defines a type of fading in the channel, namely a frequency selective fading, and an appropriate deterioration character of the telemetry link.

Practical measurements show that in general an excessive time spread and more complex multipath intensity profile determines smaller values of coherence bandwidth and coherence time. Vice versa, if an excess time delay becomes shorter and a multipath intensity profile easier, the channel capacity increases.

In one of our previous works [3] a transmission technique by means of a frequency modulated (sweep-spread) carrier has been proposed. In the technique a transmitting signal has been written as:

$$s(t) = \mathrm{Re}\{g(t)\exp[j(2\pi f_L t_c + m t_c^2)]\}, \qquad (6)$$

where *Re{·}* is a real part of the expression in curly braces, *g(t)* represents a narrow-band signal containing an information to transmit, and the exponential expression defines a sweep-spread carrier consisting of a sequence of frequency modulated fragments, where $m = \pi(f_H - f_L)/T_{sw}$ is a coefficient defining frequency gradient, T_{sw} is a duration of the frequency modulated fragment, f_L and f_H are respectively the lowest and highest frequencies, and t_c denotes a cyclical time, that can be written as:

$$t_c = \left(t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw}\right), \qquad (7)$$

where the expression $\lfloor t/T_{sw} \rfloor$ in (7) defines an operand for truncating the value t/T_{sw} to a nearest least integer.

After propagation over a multipath channel, an arriving signal has the same form as (2), but after substitution (6) in (2) and assuming that $g(t)=1$, an essentially different expression – in comparison it with (3) – can be obtained:

$$z(t) = \sum_n \alpha_n(t)\exp[j(2\pi f_L t_c + m t_c^2)]\exp[j(-2\pi \Delta f_n t_c + \varphi_n)], \qquad (8)$$

where $\pi\Delta f_n = \begin{cases} m\,\tau_{cn}, & t_c \ge \tau_{cn} \\ -m(T_{sw} - \tau_{cn}), & t_c < \tau_{cn} \end{cases}$ is provided by the time delay τ_n and signifies a frequency deviation of an *n-th* multipath arrival from a momentary frequency of the system internal reference (i.e. dispreading signal), and $\varphi_n = \begin{cases} (m\tau_{cn} - 2\pi f_L)\tau_{cn}, & t_c \geq \tau_{cn} \\ (\pi f_L + \pi f_L - m\tau_{cn})(T_{sw} - \tau_{cn}), & t_c < \tau_{cn} \end{cases}$ defines an initial phase of the *n-th* multipath arrival.

The resulting signal (8) represents as sum of multipath components shifted not only in time domain but also in frequency domain. One can also find that the frequency shift Δf_n of each component increases if carrier gradient grows. This is an important conclusion that allows to implement a mean for active adjustment of frequency shifts between a multitude of multipath components.

After dispreading the signal (8), i.e. removing the sweep-spread carrier, the resulting signal can be written as:

$$z(t) = \sum_n \alpha_n(t) \exp[j(-2\pi\Delta f_n t_c + \varphi_n)]. \quad (9)$$

The expression (9) does not represent a narrow-band signal like (4) any more. In fact it represents a sum of narrow-band signals, whereby one of them is situated in a frequency band with a mean frequency value equal to zero (if the reference signal and a correspondent multipath arrival are absolutely synchronized), and a number of other narrow-band frequency-shifted signals. It is obvious that by means of a low-pass filter (LPF) all narrow-band signals, which are situated beyond a certain LPF passband, can be suppressed. In best case, if all frequency-shifted multipath copies of the original narrow-band signal are situated beyond of the band of interest, the expression (9) transforms to:

$$z(t) = \alpha_0(t), \quad (10)$$

where zero-index corresponds to $\tau_0(t) = 0$, i.e. to a multipath arrival completely synchronized with the reference (despreading) signal in the receiver unit.

While substituting the narrow-band information signal $g(t)$, equated earlier to 1, the expression (10) will be written as:

$$z(t) = \alpha_0(t) g(t). \quad (11)$$

The absence of all interfering exponents in the expressions (10) and (11) shows that the receive signal (8) is no more affected with the frequency-selective fading that was typical to (4).

The amplitude coefficient $\alpha_0(t)$ reflects a slow (in comparison to symbol duration) oscillation of the receive signal, that is often caused, for example, by variation of the communication distance or modification of medium damping properties, *etc.* It is obvious that such amplitude fading can be easily compensated by a traditional automatic gain control circuitry.

The best case of multipath resolution described above is a quite realistic one if a frequency bandwidth of the information signal $g(t)$ does not exceed a frequency distance between the zero-index multipath and the next multipath component, i.e. $|\Delta f_0(t_c) - \Delta f_{\pm 1}(t_c)| > 1/T_s$.

If the resolution gain or the frequency distance $|\Delta f_0(t_c) - \Delta f_{\pm 1}(t_c)|$ is not enough to guarantee an entire resolution of the multipath components in frequency domain, then even a partial truncation of the multipath intensity profile simplifies the receive signal and improves one of the important statistical channel measures: coherence bandwidth. This effect is reflected in the experimental section below: a residual interference will still bring the receive signal to a frequency-selective fading, however, now not so strong as originally.

B. Non-stationary transmission

A mutual receiver/transmitter movement causes a strong channel response fluctuation resulting in a strong reverberation of receive signal. Even a small modification in relation between multipath delays causes a fast annihilation of a balance between wavelengths of interfering signals causing a wide-range variation of receive amplitude and phase values.

Such modification nominally indicates a change of frequencies of arriving multipath components, whereby the value of frequency shift of each multipath usually depends on many factors, for example, on velocity of mutual receiver and transmitter motion, on angle of reflection from moving water surface and dispersive sea bottom, on internal waves, *etc.* Taking into account such factors, a conventional constant-frequency carrier signal (4) would be represented as:

$$z(t) = \sum_n \alpha_n(t) \exp(-2\pi i (f_c + f_{dn}) \tau_n(t)), \quad (12)$$

where f_{dn} denotes a Doppler frequency of *n-th* component, which in general is random for each one of interfering arrivals. When staying in the range of telemetry frequencies the relation between a practical value of Doppler frequency and a carrier frequency is negligible, therefore a resolution of multipath components in frequency domain seems to be impossible.

Furthermore, as soon as a Doppler frequency of an interfering multipath arrival is random, the influence of a receiver/transmitter movement rarely acts as a simple frequency translation of the receive signal. In result of superposition of numerous multipath components, arriving to receiver over different paths and having different Doppler shifts, a range of Doppler frequencies distributed around an unknown average appears. Apart from a simple frequency translation, that could be trivially compensated, receiver is forced to work with continuous and complex dispersion of Doppler frequencies. A compensation for such effect is much more complicated and rarely solvable task.

It is easy to show that using the technique, proposed by authors in [3], a receive signal can be obtained in form of an attenuated but non-distorted copy of the transmitting signal $g(t)$ also in presence of random Doppler shifts.

Taking into account a Doppler shift of each component, expression (8) can be represented as:

$$z(t) = \sum_n \alpha_n(t) \exp[j(1+M_{an})(2\pi f_L t_c + m t_c^2)] \exp[j(-2\pi\Delta f_n t_c + \varphi_n)], \quad (13)$$

where M_{an} is an acoustic Mach number, defined as $M_{an}=v/c_a$, where v denotes a mutual velocity of receiver and transmitter movement along an *n-th* propagation path, and c_a is the sound speed in water. After dispreading the receive signal (removing the carrier), the expression (13) transforms to:

$$z(t) = \sum_n \alpha_n(t) \exp[j2\pi f_{dn}(t_c) t_c] \exp[j(-2\pi\Delta f_n t_c + \varphi_n)], \quad (14)$$

where $2\pi f_{dn}(t_c) = M_{an}(2\pi f_L + m t_c)$ and represents a Doppler shift after propagation along the *n-th* path, which remains in linear dependency on instantaneous frequency of the transmitting signal. Thus, the first exponent includes a Doppler shift of every *n-th* multipath arrival and the second exponent, similarly to (9), includes a frequency shift $\Delta f_n(t_c)$, which provides the effect of multipaths resolution in frequency domain. It is obvious, that in the case if the inequality $\Delta f_n(t_c) >> f_{dn}(t_c)$ satisfies over all the symbol duration T_s, a quality of multipath resolution within the symbol time will stay near to permanent. For a quantitative evaluation of the resolution an example follows, where all parameters take values, which were practically used in our experiments in shallow-water channels. While frequency gradient has an order of 10^8 Hz/s, symbol duration of 10^{-3}-10^{-4} s, carrier frequency of 10^4 Hz and acoustical Mach numbers of 10^{-3}, the frequency shift $\Delta f_n(t_c)$ remains in the range between 10^3 and 10^4 Hz. In the same time the value of $f_{dn}(t_c)$ does not exceed an order of 10^0 -10^1 Hz in entire range of frequency change (within the time of symbol duration). Thus, the frequencies $\Delta f_n(t_c)$ and $f_{dn}(t_c)$ are significantly different (three orders difference), the inequality $\Delta f_n >> f_{dn}(t_c)$ satisfies, and, after applying of an LPF to the signal (14), i.e. after separation of the zero-index component from entire spectrum of the multipath components, the resulting expression will be written similar to (11) as:

$$z(t) = \alpha_n(t) g(t) \exp[j2\pi f_{dn}(t_c) t_c]. \quad (15)$$

In general, practical values of Doppler frequency are essentially less than frequency bands (or data rates) used for underwater data transmission. This fact provides a value of *z(t),* which remains constant or changes slowly within a time interval of a symbol duration. Thus, same as in (11), *z(t)* is an attenuated copy of the transmitting signal arriving to receiver along a single path. Expression (15) differs from (12) by content of Doppler frequency associated now with only one single propagation path. The Doppler shift does not contain a sum of random Doppler shifts any more and represents a simple frequency translation of the *g(t)*. It is obvious that tracking for such frequency translations is a trivial task that can be easily solved using well-known PLL circuitries.

IV. Experimental Results

All represented materials were obtained during an experiment for investigation of physical properties of hydroacoustic communication channels, carried out February 26, 2003 in Baltic Sea near to Kiel (Germany). The purpose was to compare statistical estimations of hydroacoustic channel properties (coherence bandwidth and coherence time) obtained by means of traditional approach with and without signal processing algorithm proposed in [3].

During experiment an ultra-shallow water channel was used. The channel was characterized by smooth depth change from 15 m at the transmitter side to 10 m at the receiver side. Transmitting and receiving transducers were installed under keel of a boat and under a stationary platform at 1.5 m and 4.5 m depth correspondingly. Communication distance was 1700 m. The signal transmission was carried out stationary, however, in result of slight pitch, roll and drift of the boat, instant values of transmitter/receiver mutual movements laid in the range of 1 m/s. The sea condition was smooth and the wind strength was about 1-2 m/s. Transmitter and receiver orientation experienced slight variation during the transmission. The source level achieved 192 dB relatively to 1μPa/m. Signal to noise ratio comprised 14-15 dB at the receiver side. The transmitted sequences consisted of 500 frequency-modulated signals with duration of 2048 μs and were separated from each other with pauses of 20 ms. Transmitted signals occupied an effective frequency band 28 kHz around slightly pronounced resonance in vicinity of 57 kHz.

Broadband piezoceramic transducer PCT Device 2 (manufactured by PCT Acoustic Transducers Inc., Great Britain) was used as acoustic signal source. In transmission mode the transducer had a smooth TVR curve with non-linearity of 4 dB in operating frequency range.

As result of deep damping the transmitter had low efficiency – not more than 1%. To reach the transmission source level of 192 dB a high driving voltage up to 3000 V was used. To provide a reliable decoupling and receiver high-voltage protection, several original electronic devices were developed with authors of the paper.

All the electronic of the electro-acoustic section was mounted in a sealed Al-Mg underwater container. To reduce an induced noise, the acoustical transducer was directly connected to the input of a transmit/receive switch, which output had in parallel a preamplifier assigned for received signals and a power amplifier assigned for transmitted ones. A DC-DC converter based on VICOR VI-214 was used as the power supply. Primary DC supply was conducted via connection cable from an external 24V battery placed on the boat.

To form, transmit and process signals, an industrial portable computer based on an Intel Pentium III processor was used. The computer was installed in an ACME splash-proof frame and equipped with a National Instruments data acquisition board. Transmitting signals were fed in analogous form to the power amplifier placed in the hermetic underwater container. After power amplification the signals were submitted to the acoustic transducer for transmitting them in water.

To receive the signals a similar PCT hydrophone (Device2) was also used on the receiver side. Input signals were pre-amplified, filtered and digitized with a sample rate of 500 kHz. Functions of pre-processing, time selection, demodulation and registration of received information were carried out with a similar computer as that one on the transmitter side.

A. Channel characterization

Fig. 1 shows a collection of time spreads for a sequence of signals received. Multipath intensity profile is represented with 6-7 multipath components. Time delays between the multipath components stayed in the range of 70-200 mcs. Power fluctuation of the multipath arrivals run up to about 10 dB. Modification of the multipath intensity profile occurred within a time interval of 1-1.5 s. Maximum excess of time delay remained constant and comprised about 2 ms.

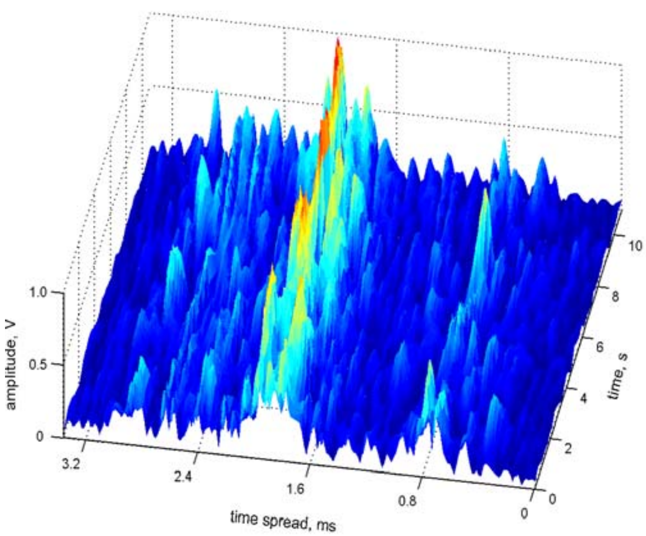

Fig. 1. Fluctuations of multipath intensity profile in the shallow water channel (telemetry distance: 1700 m).

B. Processing of signals received

After synchronization of the internal receiver reference with the time of a most powerful arrival a following preparation was carried out. Firstly, an evaluation of the maximum time spread in the telemetry channel took place. An area of interest covered an interval of time, in which the power of multipath components remained not less than –15 dB in relation to the most powerful arrival. Secondly, time spread signals of the receive sequence were extracted one after another from entire input data (vector of digitized samples) and placed one under another, thus creating a rectangular matrix of 500 lines (correspondingly to the number of frequency modulated signals in the sequence transmitted).

To evaluate a frequency transfer function of the telemetry channel, a multi-band filtering was carried out. A relatively narrow-band filter of 5 kHz bandwidth was applied to the broadband signal (40-80 kHz) many times beginning from the left cutting frequency of 40 kHz towards 80 kHz with a step of 1 kHz. For evaluation of the multipath intensity profile $S(\tau)$ an autocorrelation function was calculated for every one of the 5 kHz sub-bands. Creating Fourier image of the $S(\tau)$ a conventional estimation of the two-frequency correlation function $|R(\Delta f)|$ was carried out. Correlation level of 0.5 was used as the critical line for calculation of a coherence bandwidth in vicinity of each frequency of the entire range between 40 and 80 kHz. A sequence of such coherence bandwidth values allowed to evaluate a frequency transfer function of the current telemetry channel. Fig. 2 represents the frequency transfer function with a dashed line. As one can see the coherence bandwidth for each frequency of the evaluated 40 kHz band has a value from the range between 3 and 6 kHz.

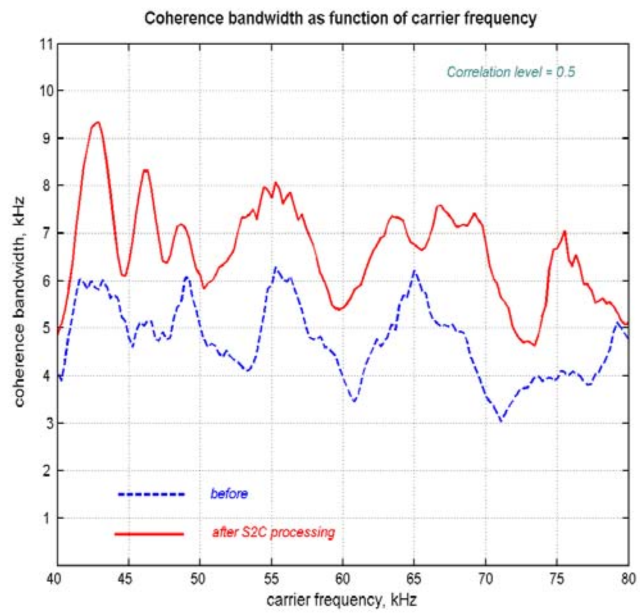

Fig. 2. Comparison of frequency transfer functions.

To achieve advances of the method called S2C Com (sweep-spread carrier communication) [3] a truncation of multipath intensity profile (time spread) was completed as follows. Provided that an accurate synchronization of the dispreading signal with the most powerful multipath arrival has taken place, the receive signal was despreaded so that the central frequency of the “useful” (most powerful) multipath component was equal to zero. In the same time a number of spectral lines with non-zero values of their central frequencies appeared and corresponded to “harmful” multipath arrivals. As shown above, they were shifted not only in time but also in frequency in relation to the useful component. For elimination of their influence a low-pass FFT-filter with a cutting frequency of 6 kHz was applied.

Afterwards, the filtered signal was multiplied with the dispreading signal again, thus reconstructing a spread spectrum signal, however, containing now a reduced (filtered) number of multipath arrivals.

An evaluation of a frequency transfer function after such processing is represented in Fig. 2 with a solid line. A comparison of the dashed line and the solid one shows a considerable improvement of coherence bandwidth. In fact, approximately a factor of two has been achieved. This result is an important consequence of the time spread truncation achieved due to use of the S2C Com technique. It is obvious that an increasing coherence bandwidth means an increasing channel capacity and correspondently an increasing speed of data transmission.

It is known that signal dispersion and coherence bandwidth describe statistical channel features in terms of time spread. However, they do not give any information concerning time fluctuations that signals experience on the receiver side. Such fluctuations become notable even in case of marginal mutual movements of source, receiver and objects in the channel and, therefore, are always present and comprise an important channel characterization. For quantitative evaluation of an instationary channel behavior a time-spatial correlation function $|R\ (\Delta t)|$ was estimated, which represented a correlation degree between an impulse response upon a probe signal that was transmitted at time t_1, and an impulse response upon the same probe signal that was transmitted at time t_2, whereby $\Delta t = t_2 - t_1$. While executing such procedure in relation to the signals of the arriving sequence, a direct measurement of the $|R\ (\Delta t)|$ was carried out. A series of $|R\ (\Delta t)|$ estimates defined a (dashed) line in Fig. 3. The coherence time was measured also on the correlation level of 0.5 and comprised a value of 3.2 s. This value represents a quite long time for a telemetry system, however, if one takes into account the significantly calm weather conditions during the experiment, much shorter coherence times must be expected during communication over more complicated channels of practical interest.

To evaluate the effect, which can be achieved owing to advances of the S2C Com technique, a series of coherence time estimates were made on the base of the same signal sequence after the truncation of their multipath intensity profile similarly to procedure that was described above. The result is represented with a solid line in Fig. 3. A comparison of two lines visualizes a significant improvement of the coherence time that was obtained after the truncation procedure. This result is important for further optional implementations, i.e. more efficient realization of a transmission protocol, specification of longer (information) packet lengths, shorter packets of service information *etc.*, what finally would determine a more efficient time and frequency use of the available channel.

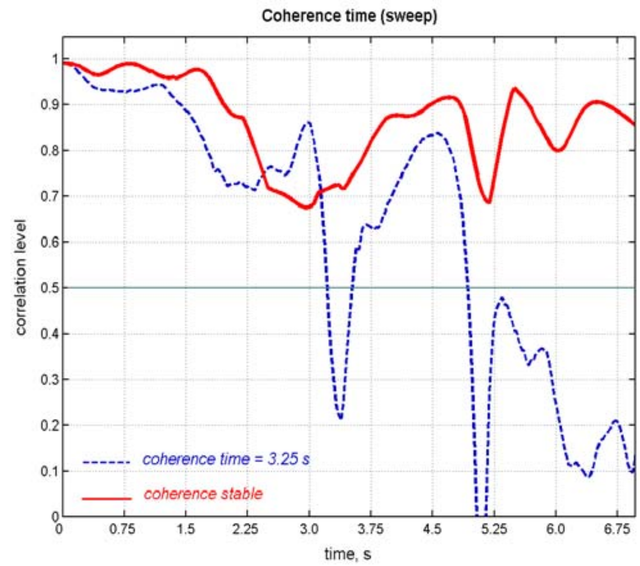

Fig. 3. Comparison of coherence time intervals.

C. Frequency efficiency

According to published data [1], a frequency efficiency of traditional incoherent systems usually remains between 0.01 and 0.15 bit/Hz. An exception represents the only system with a maximum value of 0.24 bit/Hz, whose bit error rate, however, comprises a critical level of 10^{-2}.

For efficiency evaluation of the proposed technique in terms of its frequency usage, an experiment was carried out, where said features of the S2C Com technique were implemented in a communication system. Transmission was conducted in shallow water channels with depths between 10 and 15 meters and distances between 1000 and 2000 meters, inclusive the channel that was described above. Data rates achieved laid in interval between 3.8 and 14.6 kbps. Bit error rate fluctuated between 10^{-4}-10^{-2}. Golay coding scheme together with a CRC32 data verification allowed an execution of a successful data exchange during a quite long time (in different cases between tens of seconds and several minutes). This represents the fact, that such important feature of incoherent system as robustness is inherent also to the S2C Com technique and signifies one of its important traits. A ratio between the data rate and the frequency band used for data transmission gives an estimate of frequency efficiency, which in our system comprises an experimental value between 0.14 and 0.52 bit/s. As follows from comparison of this value with those that were published for conventional incoherent systems, an implementation of the S2C Com determined a two times increase of efficiency of frequency usage providing correspondingly improved values of achievable data rates for incoherent communication over shallow water acoustic channels.

V. Conclusions

Data rates of incoherent underwater telemetry systems can be at least doubled due to implementation of the S2C

Com technique, whose important trait consist in transmission of a spread spectrum signal. The technique carried out the necessary spectrum spread by means of multiplication of a transmitting signal onto a linear chirp with a large frequency gradient, what allowed to achieve a complete or at least a partial resolution of multipath arrivals and, in this way, an opportunity to filter the arrivals in frequency domain and, depending on a data rate, a chance to eliminate completely or partly an influence of the multipath interference on the receive signal.

Experimental data confirmed the expected effectiveness of the technique and demonstrated a significant improvement of its statistical indices, specifically a considerable enhancement of coherence bandwidth and coherence time of horizontal shallow water channels. The experimental results of data transmission over the 1700 m channel displayed not only high data rates and long time intervals of robust data exchange, but also a significant efficiency improvement providing an advanced frequency usage.

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