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SEPARATION OF TIME-VARYING MULTIPATH ARRIVALS BY CONVERTING THEIR TIME DELAYS INTO THEIR FREQUENCY REALLOCATIONS

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Multipath propagation causes the transmitted signal to take numerous, time-varying different-length paths to receiver. Exploitation of conventional frequency-constant carrier signals for communication over underwater acoustic channels typically shows that intricate mutual time variations of multipath arrivals create a serious problem for equalizers to compensate for non-stable interferences. Communication over such channels can be, however, substantially improved by using not a conventional constant-frequency carrier but a carrier consisting of a sequence of steep sweeps. The method provides significant processing improvement enabling clear separation of multipath arrivals by converting their time delays into their frequency reallocations. When despreading the signal, the best suitable multipath can be filtered not as traditionally in time domains, applying complex equalizers, but in frequency domains via usual band-pass filters. An important aspect is that every multipath is separated together with its individual time-varying phase impairments, obtained with the signal during its propagation over a certain path, whereas signal impairments, specific for a given path, are completely separated from other signal impairments delivered by the signal during its propagation over every different path.

INTRODUCTION

A major problem for achieving reliable and high rate underwater acoustic (UWA) communication is the severe time-variable intersymbol interference (ISI) strongly introduced in horizontal shallow water channels. Reflections from channel boundaries and diverse objects dominate the multipath structure. The structure becomes geometry specific and not predictable. Time variant multipath propagation is recognized as a basic channel characteristic, and single path temporal fluctuations are considered as primary performance problems. Well-known fact (e.g. [1]) is that not the multipath propagation itself introduces the fundamental performance limitation for acoustic telemetry system; rather single path temporal fluctuations are primary performance problems. This concern stays perfectly true so far as a time-based filtering approach, like equalization based on a tapped delay line filter, takes place. Temporal phase/frequency impairments, obtained by the signal during its propagation over different paths, are coupled at receiver so that no accurate time-domains filtering can be accomplished. The longer the time spread and stronger dynamic influence, the less accuracy that can be achieved.

Multitude of contemporary UWA communication approaches encounters numerous performance limitations, induced with such conditions, what motivates the search for a strategy, by which the time-varying ISI can be effectively treated.

In the paper, an approach, recently developed in [2] is suggested, where the separation of every single path occurs not in time but in frequency domains by means of usual band-pass filters.

A significant advantage of the method consists in the fact that an accurate multipath separation can be easily achieved without application of complex processing structures like adaptive equalizers. Instead, a simple pre-processing unit will be implemented into receiver section capable to transform a complex time-varying multipath mixture to a combination of frequency spaced multipath arrivals making use of the specific sort of carrier signals (sweep-spread carrier) applied. An important aspect is to the effect that every multipath signal is separated together with only its individual time-varying (phase) impairments, obtained with the signal during its propagation over a certain path. That is, signal impairments, specific for a given propagation path, are completely separated from signal deformations obtained by the signal during its propagation over every different path. Hence, each single time-varying multipath arrival can be processed individually and, thus, in the best form for further evaluation of its information symbols.

In section II, the sweep-spread carrier (S2-carrier) behavior in a UWA channel is represented. The off-line processed experimental results are presented in the section III, followed by conclusions.

1. Peculiarities of the S2-carrier behavior in a UWA multipath channel

The approach used is associated with spread-spectrum communication methods. Its main peculiarity is that a phase-encoded symbol $s(t)$ is modulated not onto commonly used frequency-constant or stepped varying carrier but onto a carrier, which experiences permanent frequency variations [2].

The S2-carrier (applied in the experimental work later shown) consisted of a succession of linear sweeps with frequency variations from ω_L to ω_H within a time interval T_{sw}. All the sweeps were uniformly produced in linear manner with rapid frequency variation following each other successively without any gap between them.

To show the expected behavior of such carrier, some expressions are given here to compare the transmitting signal and this one after the propagation over an UWA channel having multipath.

The S2-carrier transmitted over the channel can be written as:

$$c(t) = A_c \exp[j(\omega_L (t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw}) + m(t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw})^2)], \qquad (1)$$

where A_c is the amplitude, $m = (\omega_H - \omega_L)/2T_{sw}$ is a coefficient denoting the frequency variation rate, ω_L and ω_H denote respectively the lowest and highest angular frequencies, T_{sw} is the sweep duration, and the term $\lfloor t/T_{sw} \rfloor$ denotes the operand for truncating the value to the nearest least integer.

Another notation form of (1) can involve the equation:

$$(t - \left\lfloor \frac{t}{T_{sw}} \right\rfloor T_{sw}) = \left\{ \frac{t}{T_{sw}} \right\} T_{sw}, \qquad (2)$$

what can be interpreted in (1) as an actual cycle time with the cycle duration T_{sw}.

The peculiarity of the carrier (1) can be accentuated in mathematical terms through the presence of the quadratic member in the parentheses.

If modeling the signal propagation over the UWA channel, the receiving signal consists of a number of delay elements with τ_i, denoting time intervals between two successive multipath arrivals, and a number of multiplication elements with coefficients V_i taking into account possible attenuations on interfering multipath signals. If both the $c(t)$ and $s(t)$ have unit amplitudes, and, every attenuation coefficient V_i and delay element τ_i stays constant over the entire transmission time, then, after propagation along different paths in the underwater medium, the transmitted signal $x(t)=s(t)\cdot c(t)$ comes to receiver in the form:

$$y(t) = V_0 x(t) + \sum_i V_i x(t-\tau_i) + n(t), \tag{3}$$

where $x(t)$ is defined above and $x(t-\tau_i)$ is written as follows:

$$x(t-\tau_i) = s(t-\tau_i)\exp[j(\omega_L \left\{\frac{t-\tau_i}{T_{sw}}\right\} T_{sw} + m(\left\{\frac{t-\tau_i}{T_{sw}}\right\} T_{sw})^2)], \tag{4}$$

and $n(t)$ is the white noise. It is evident that

$$\left\{\frac{t-\tau_i}{T_{sw}}\right\} T_{sw} = \begin{cases} t_c - \tau_{ci}, & t_c \geq \tau_{ci} \\ T_{sw} + t_c - \tau_{ci}, & t_c < \tau_{ci} \end{cases}$$

where $t_c = \left\{\frac{t}{T_{sw}}\right\} T_{sw}$ is the cycle time defined in (2), and $\tau_{ci} = \left\{\frac{\tau_i}{T_{sw}}\right\} T_{sw}$ is a fractional part of the time delay related to the sweep duration T_{sw}. Thus, every delayed arrival represented in the second member of (3) can be rewritten as:

$$x(t-\tau_i) = \begin{cases} s(t-\tau_i)\exp[j(\omega_L(t_c-\tau_{ci}) + m(t_c-\tau_{ci})^2)], & t_c \geq \tau_{ci} \\ s(t-\tau_i)\exp[j(\omega_L(T_{sw}+t_c-\tau_{ci}) + m(T_{sw}+t_c-\tau_{ci})^2)], & t_c < \tau_{ci} \end{cases} \tag{5}$$

After transformation of the expression (5) each delayed arrival can be then written as:

$$x(t-\tau_i) = s(t-\tau_i)\exp[j(\omega_L t_c + m t_c^2)]\exp[j(-\Delta\omega_i t_c + \varphi_i)], \tag{6}$$

where, $\Delta\omega_i = \begin{cases} 2m\tau_{ci}, & t_c \geq \tau_{ci} \\ -2m(T_{sw}-\tau_{ci}), & t_c < \tau_{ci} \end{cases}$ signifies the frequency deviation of an *i-th* multipath arrival provided by the delay τ_i, and $\varphi_i = \begin{cases} (m\tau_{ci} - \omega_L)\tau_{ci}, & t_c \geq \tau_{ci} \\ (\omega_L + \omega_L - 2m\tau_{ci})\frac{T_{sw}-\tau_{ci}}{2}, & t_c < \tau_{ci} \end{cases}$ is the phase of the *i-th* multipath arrival.

The term with $i = 0$ in the summation (3) represents an attenuated version of the original signal, and the other term signifies the multipath diversity of its delayed, attenuated and frequency shifted reproductions. Especially important in (6) is that at any instant all the interfering multipath arrivals have different frequencies spaced by $\Delta\omega_i$ from each other. Exactly this behavior we shall see later shown in experiment in Fig. 2.

This feature is central for the approach: by introducing the S2-carrier, a time spread of the signal in a multipath channel can be converted into a frequency reallocation of individual multipath arrivals over a definite spectrum area. By achieving an appropriate frequency separation of the multipath arrivals, considerable frequency based "rectification" of the receiving signal can be attained, whereby each desirable spectrum component (multipath arrival) can be selected and processed individually [2]. Thus, any multipath distorted signal can be represented with one single multipath arrival (one single spectral line), i.e. in the best form for processing and consequent evaluation of an encoded parameter.

Differential PSK receiver: After filtering out a suitable spectral line (multipath arrival), decoding starts. In the experiments later shown, a PLL local oscillator could be efficiently used since the deeply suppressed multipath arrivals could not seriously influence the loop stability. However, in the off-line processing, a simple differential 4-point PSK (QPSK) receiver was used. Demodulation was performed by comparing phase from symbol to symbol. The scatter diagram later shown were generated by such a demodulator.

2. Experimental results

In August 2000, some 1.5 GB data were acquired in shallow water channels in a lake (Baggersee near Bremen, Germany). In the lake, the communication distance was short (108 m), but because of rather small lake dimensions (maximum diameter 300 m), the interferences were especially severe. The transmitted signals were successfully decoded. In the following section, some results of the Baggersee experiment will be presented. The data shown was taken from one of the acquired 1-second data blocks, which were used for off-line processing to evaluate the method's performance.

Experimental Setup: Transmit and receive transducers were mounted respectively at ~5 m and ~6.5 m below the water surface from stationary platforms. The cite depth changed gradually from ~12 m at transmitter to ~17 m towards receiver. The horizontal radius was about 108 m. The lake conditions were rather calm; the wind strength was about 3-4 m/s. The source power has been varied, so that different SNRs were available for subsequent analysis. To imitate a source/receiver motion, the transmitting hydrophone was permanently moved during the experiment with a maximum speed of 2 m/s.

The S2-carrier occupied the frequency range from 40.1 up to 90.1 kHz, and had the sweep cycle time of 10 ms, thus making a frequency gradient of 5 kHz/ms. Fig. 1 shows a fragment of the S2-carrier (sweep sequence) recorded on the distance of 2 m from the transmitting hydrophone.

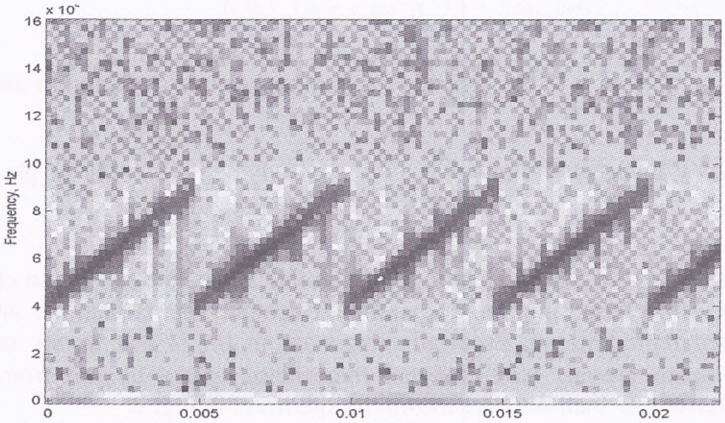

Fig. 1. A fragment of the S2-carrier close to transmitter.

For the broadband communication applied, a new special broadband transmitter has been used: a PCT model (directional, 52°), which has a flat transmitting voltage response (TVR) in the range between 45 kHz and 85 kHz with a maximum deviation of 3 dB from its central value. As one can conclude from the figure, the level of the transmitted signal stayed approximately equal over the broad frequency band.

The modulation format was differential QPSK with the bit rate of 4 kb/s. Thus, the symbol duration was 0.5 ms; every sweep of the sequence carried 20 symbols. The data block duration was 1.0 second long. The signal shape was rectangular. The received signal was sampled at 320 kHz rate.

Fig. 2 represents a fragment of the received signal. As one can see, in result of multipath propagation some multipath arrivals follow every sweep. This occurs exactly in such the manner described in the section II. The arrows show time instances, when in each case the second arrival (having rather significant power) comes to receiver. The more detailed consideration of the multipath structure is given later, after a dispreading procedure has been accomplished.

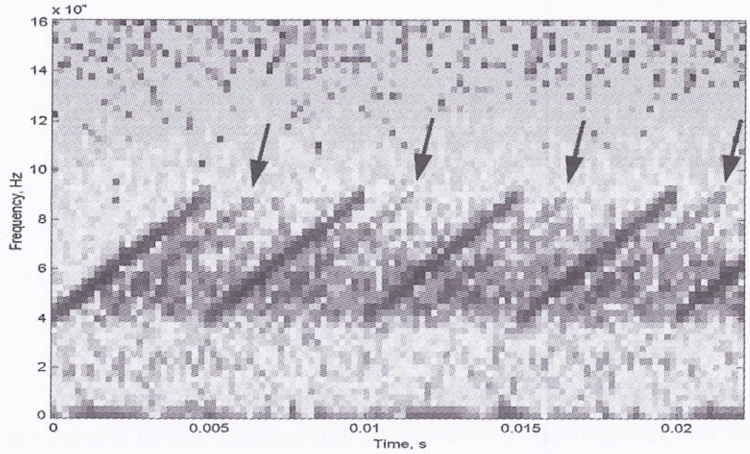

Fig. 2. A fragment of the received S2-signal 108 m away form transmitter.

Despreading parameters

In order to enable subsequent system components to work with a "rectified" version of the received signal, a dispreading procedure takes place. After estimation of a precise timing parameter (obtained e.g. based on maximum likelihood estimation principles), the received signal is multiplied with a locally generated version of the S2-carrier – a gradient heterodyne signal – having the same steepness (5 kHz/ms) and the same sweep cycle (10 ms), however, being produced with an initial frequency of 50 kHz higher than that of the transmitted signal (i.e. in range from ω_L + 50 kHz to ω_H + 50 kHz). Hence, the main spectral line of the IF spectrum, being obtained with the correct timing, had its location within a filter window with the central frequency of 50 kHz, as well (later in Fig. 4).

Channel characterization

To gain insight into the channel characteristics, a series of channel estimations was performed initially by transmitting unmodulated S2-carrier sweeps over the channel. After despreading and low-pass filtering, the IF spectrum reflected the multipath delay spread structure of the channel.

Fig. 3 shows the snapshot of the multipath structure obtained for the unmodulated sweep with the duration of 10 ms. As one can see, the structure consisted of about 10 multipath arrivals. The total multipath delay spread was estimated about 8 ms. In frequency domains, the distance between two first multipath arrivals comprised a value of 6.7 kHz. That is, the delay between them was about 1.3 ms. This delay didn't resemble that one, which was obtained under similar conditions in previous experimental trails (see in [2]), and didn't correlate with its estimation of 325 μs (for the surface reflected path if using simple geometry). However, it is reasonable to suggest that such long interval is to the fact of applying the mono-directional transmitter with the directivity angle of only 52° (whereas the previous experimental set-up comprised an omni-directional transmitter). The difference between them was about 16 dB. Such considerable loss can be hardly explained by a suggestion that the second arrival was a bottom bounce. The bottom was hard and the reflection angle was very small. Obviously the second arrival had to propagate over a much longer path than the first one.

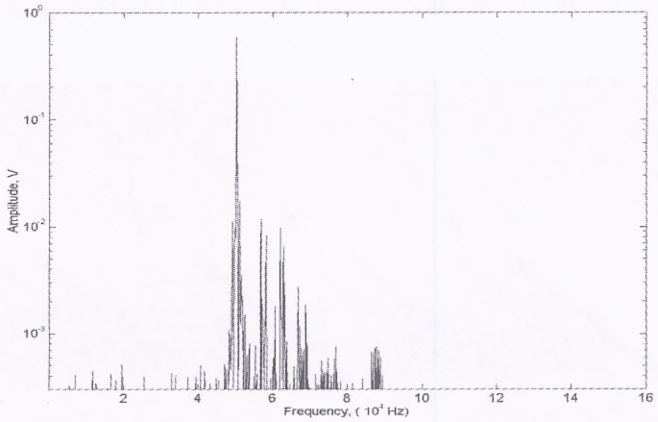

Fig. 3. Spectrum snapshot of the intermediate frequencies.

To separate the most powerful arrival from the spectrum (or to prevent an influence of neighboring spectral lines), a BPF filter was applied. The filter was of the least square FIR type and contained 50 coefficients. The filtering window width was 5 kHz, whereby the low and high cut frequencies were set on 47.5 and 52.5 kHz, respectively. Fig. 4 shows a fragment of the rectified signal (intermediate frequency). The signal does not contain any multipath arrivals, that is, the resulting signal, which is fed to the differential QPSK parameter estimator, is represented with only one single path.

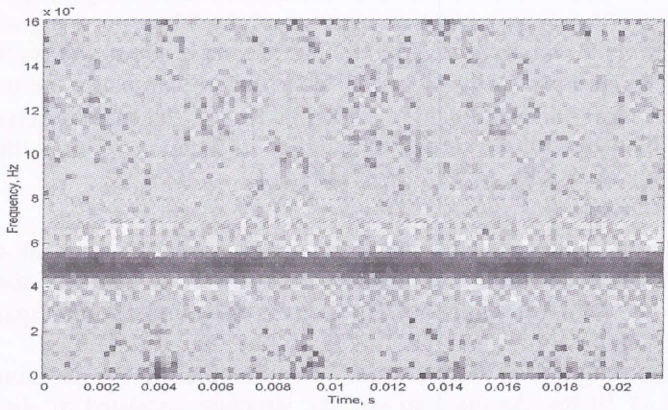

Fig. 4. A fragment of the rectified signal (intermediate frequency).

Performance results

Fig. 5 shows the demodulation results obtained with differential QPSK signals transmitted over the Baggersee channel using the S2-carrier. The main multipath signal had an SNR of more than 10 dB. The scatter plot of the estimated data symbols on which the decisions were performed shows an open eye pattern. However, in the block of 2000 symbols there were detected two errors.

Although long-trail tests were still not carried out, we could at least evaluate the error probability for this case. Letting the phase dispersions in every sector to be normal around its central value, the calculated error probability P_e estimated was 5 10^{-4}, thus satisfying the usual in UWA communication requirement.

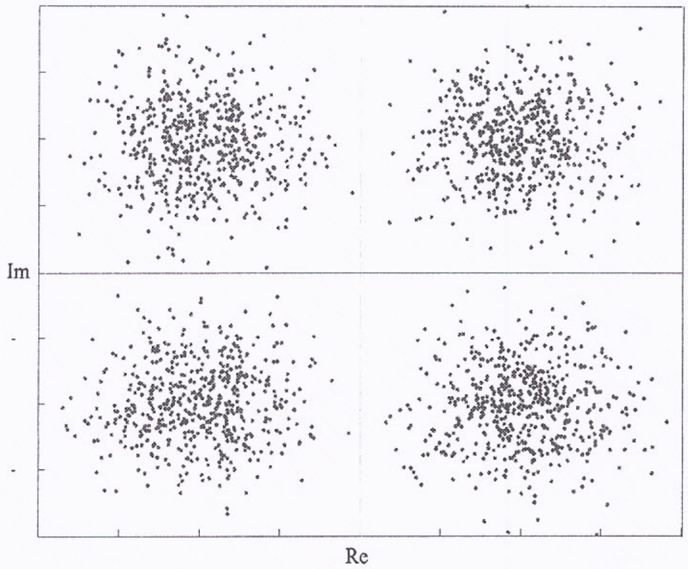

Fig. 5. Demodulation results.

Conclusions

The theoretical as well as the experimental results conclusively demonstrate the successful operation of the S2C method in reducing the effects of multipath propagation in an underwater acoustic telemetry link. Especially in shallow water channels, communication can be substantially improved by the implementation of the S2C method.

The primarily important feature is that filtering occurs not in time but in frequency domains. Using the property of acoustic signals to propagate under water with relatively low speed, the method allows to extensively space all multipath arrivals in time-frequency area by converting their time delays into their frequency reallocations provided that sufficiently steep sweeps are applied.

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