MULTIPATH-DOPPLER DIVERSITY OF OFDM SIGNALS IN AN UNDERWATER ACOUSTIC CHANNEL

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ABSTRACT

High-speed communications over the underwater acoustic channel are difficult due to time-varying multipath propagation and Doppler scattering. These phenomena, however, can be effectively used for joint multipath-Doppler diversity of received signals similarly to multipath diversity in a conventional Rake receiver. We present a new signal processing technique for data transmission over fast fading underwater acoustic channel by using OFDM signals. This technique exploits multipath-Doppler diversity which is based on the channel model as a sum of macro-rays characterised by delays, Doppler parameters and transfer functions. Delay and Doppler estimation involves calculation of the cross-ambiguity function for a pilot signal; transfer function estimation exploits frequency domain B-spline approximation. Experimental results demonstrate high BER performance of the proposed algorithm for various propagation scenarios.

1. INTRODUCTION

Multipath propagation and Doppler scattering can be effectively used for joint multipath-Doppler diversity of received signals with different types of modulation. Orthogonal Frequency Division Multiplexed (OFDM) signals are attractive for implementation because they lead to relatively simple channel estimation and demodulation algorithms. In [1] the frequency-spatial diversity reception of OFDM signals for short distance underwater propagation was studied. In [2] and [3] we have presented experimental results relating to joint multipath-Doppler diversity of spread-spectrum OFDM signals with orthogonal modulation by Walsh-Hadamard functions; the adaptation of the receiver to Doppler scattering has been shown to have improved the demodulation performance in different propagation scenarios. Detailed investigation has shown that the bit error rate (BER) in such a receiver depends basically on signal-to-noise ratio (SNR) and is practically independent of other channel characteristics [4]. Recently it has been proposed to use multipath-Doppler diversity for wireless mobile communications in fast fading channels [5].

In this paper we consider frequency diversity transmission and joint multipath-Doppler diversity reception of the OFDM signals. We present an algorithm for receiving the signals and investigate its performance in real propagation scenarios. The paper is organised as follows. In Section 2 the signal model is presented. Section 3 describes the channel model with multipath and Doppler scattering. Section 4 describes signal processing in the receiver, including estimation of delays and Doppler parameters, spline-approximation of the channel transfer function, combining of the diversity signals and decoding. Section 5 presents experimental results. Section 6 contains conclusions.

2. TRANSMITTED SIGNAL

The transmitted OFDM signal can be modeled as

$$s(t) = A \sum_{k=0}^{N-1} cos[\omega_k t + \phi(k)] \quad (1)$$

where N is the number of frequency components (in our experiments, $N = 1024$), A is the amplitude, $\omega_k = 2\pi f_k$, $f_k = f_c - F/2 + k/T_s$, f_c is the central frequency, T_s is the symbol duration and $F = N/T_s$ - the frequency bandwidth of the transmitted signal. The function $\phi(k)$ defines the phase modulation of the frequency components: $\sqrt{2}\exp\{j\phi(k)\} = a(k)M_2(k) + jM_1(k)$ where $j = \sqrt{-1}$ and $M_1(k)$ is the spectrum of a pilot signal used by the receiver for channel estimation. The spectrum of the information signal is $a(k)M_2(k)$. The sequence $M_2(k)$ provides randomisation of the transmitted signal; as a result, the signal waveform $s(t)$ is similar to a realisation of a Gaussian noise process. $M_1(k)$ and $M_2(k)$ are different m-sequences of length N; the sequences $a(k)$, $M_1(k)$ and $M_2(k)$ are binary with values ± 1. For frequency diversity each data bit d_m, $m = 0, \ldots, N/Q - 1$, is simultaneously transmitted on Q frequencies: $a(m + iN/Q) = d_m$, $i = 0, \ldots, Q - 1$. We consider Q-branch frequency diversity with $Q = 2^n$, where n is integer with $n = 0, \ldots, 7$. Overall data transmission consists of a number of consecutive OFDM symbols. The data rate is F/Q bps.

3. CHANNEL MODEL

We consider the channel model [3], [4]

$$x(t) = \sum_{l=1}^{L} \int_{-\infty}^{\infty} s(\eta_l t - u) h_l(u - \tau_l) du + \xi(t). \quad (2)$$

There are L macro-rays with Doppler parameters η_l, delays τ_l and impulse responses $h_l(t)$; $\xi(t)$ is additive white Gaussian noise. The model (2) for $h_l(t) = \delta(t)$, where $\delta(t)$ is the Dirac delta function, and $|\eta_l - 1| \ll 1/(T_s F)$ results in

$$x(t) = \sum_{l=1}^{L} s(t - \tau_l) e^{j2\pi f_l t} + \xi(t) \quad (3)$$

where $f_l \approx f_c(1/\eta_l - 1)$. The model (3) is a basis for joint multipath-Doppler diversity in fast fading mobile radio channels

[5]. From (2), it follows that matched-filter processing of the received signal can be performed separately for each macro-ray and then results can be combined similarly to combining the multipath components in a Rake receiver [6].

4. SIGNAL PROCESSING IN THE RECEIVER

Algorithm of signal processing in the receiver includes 1) end-front processing; 2) estimation of the delays τ_l and Doppler parameters η_l; 3) estimation of transfer functions $H_l(\omega)$ corresponding to the impulse responses $h_l(t)$; 4) diversity combining and data decoding.

4.1. End-front processing

The received signal $x(t)$ is filtered in the frequency band $[f_c - F/2, f_c + F/2]$, sampled at the frequency $f_s = 1/T = 4f_c$ and, over each interval of duration T_s, the samples are used for calculation of complex envelopes

$$z_q(n) = \sum_i x(iT)e^{j2\pi f_c iT/\eta_q} g[nT_s\eta_q/N - iT] \qquad (4)$$

where $g(t)$ is impulse response of a discrete lowpass filter with a frequency bandwidth of $F/2$ and $n = 0, \dots, N-1$. The frequencies $f_c(q) = f_c/\eta_q$ cover the Doppler frequency range $[f_c - F_D, f_c + F_D]$: $f_c(q) = f_c + q\Delta f/2$, where $q = -N_D, \dots, N_D$, $(2N_D + 1)$ is the number of Doppler channels in the receiver; $\Delta f = 1/T_s$ is the frequency resolution of the signal, and $F_D = \Delta f N_D/2$.

4.2. Estimation of delays and Doppler parameters

For estimation of the delays and Doppler parameters, the cross-ambiguity function is calculated; the envelopes $z_q(n)$ are correlated with the pilot-signal described by the spectral sequence $M_1(n)$:

$$Z_q(k) = \sum_{n=0}^{N-1} z_q(n)e^{-j2\pi kn/N}, \qquad (5)$$

$$y_q(n) = \frac{1}{N}\sum_{k=0}^{N-1} Z_q(n)M_1(k)e^{j2\pi kn/N}. \qquad (6)$$

The sequence $|y_q(n)|$ is q-th section of the cross-ambiguity function. Since variations of the delays and Doppler parameters are slow with respect to variations of the complex amplitudes, the non-coherent average of the cross-ambiguity function is used

$$V_q^\gamma(n) = (1-\alpha)|y_q(n)| + \alpha V_q^{\gamma-1}(n) \qquad (7)$$

where the index γ relates to the γ-th processed signal in the communication session. The parameter α $(0 < \alpha < 1)$ when close to unity allows us to reduce the influence of the noise $\xi(t)$ upon the estimation accuracy. Among the values $V_q^\gamma(n)$, the first L maxima are selected; the positions of the maxima (n_l, q_l) give the estimates of the delays $\hat{\tau}_l = n_l T_s f_c/(N f_c(q_l))$ and Doppler parameters $\hat{\eta}_l = f_c/f_c(q_l)$. The selection of the macro-rays is connected with the algorithm of estimating the transfer functions.

4.3. Estimation of transfer functions of macro-rays

Estimation of transfer functions is based on frequency domain spline-approximation. The algorithm can be described as follows. For each macro-ray the spectral sequence

$$\bar{Z}_l(k) = \sum_{n=0}^{N-1} z_{q_l}(n - n_l)e^{-j2\pi kn/N} \qquad (8)$$

is calculated. It should be noted that $\bar{Z}_l(k)$ in (8) is different from $Z_q(k)$ in (5) since in $\bar{Z}_l(k)$ the delay has been compensated. This is important because the transfer function can vary considerably during one OFDM symbol, so that the estimate of the transfer function should be performed over the same time interval, which will be later used for diversity combining. The estimate $\hat{H}_l(\omega)$ of the transfer function $H_l(\omega)$ is

$$\hat{H}_l(\omega) = \sum_{r=0}^{R} c_r^{(l)} B_r(\omega). \qquad (9)$$

The expansion coefficients $c_r^{(l)}$ are determined as $c_r^{(l)} = \sum_{m=0}^{R} b_{rm}\xi_m^{(l)}$, where the matrix $\{b_{rm}\}$ is the inverse of the matrix with elements $a_{rm}^{(l)} = \sum_{k=0}^{N-1} B_r(\omega_k)B_m(\omega_k)$, and $\xi_m^{(l)} = \sum_{k=0}^{N-1} M_1(k)\bar{Z}_l(k)B_r(\omega_k)$. The basis functions $B_r(\omega) = B(\omega - 2\pi f_c + \pi F - r\Omega)$, $r = 0, \dots, R$, $\Omega = 2\pi F/R$, are built upon the cubic B-spline

$$B(\omega) = \begin{cases} \frac{1}{6}\left(2 - \frac{|\omega|}{\Omega}\right)^3 - \frac{2}{3}\left(1 - \frac{|\omega|}{\Omega}\right)^3, & 0 \le |\omega| < \Omega, \\ \frac{1}{6}\left(2 - \frac{|\omega|}{\Omega}\right)^3, & \Omega \le |\omega| < 2\Omega, \\ 0, & |\omega| \ge 2\Omega. \end{cases}$$

In [7] the mean square error

$$\delta^2 = \frac{E\{\sum_{k=0}^{N-1} |H_l(\omega_k) - \hat{H}_l(\omega_k)|^2\}}{\sum_{k=0}^{N-1} |H_l(\omega_k)|^2}$$

was investigated, where $E\{\cdot\}$ denotes statistical expectation. The error can be presented as $\delta^2 = \delta_a^2 + \delta_s^2$. The approximation component δ_a^2 depends on the basis functions $B_r(\omega)$ and differential properties of $H_l(\omega)$, which in turn depends on maximum delay of the impulse response $h_l(t)$; this component can be neglected if the maximum delay is less than $R/(2F)$. The processing of the l-th macro-ray involves multipath signal components with delays from the range $\theta_l = [n_l - R/2, \dots, n_l + R/2]$. Therefore, the following procedure has been used for selection of macro-rays:

$$\bar{V}_{qn}^{(1)} = V_q^{(\gamma)}(n); \quad (q_l, n_l) = \arg\max_{q,n}\{\bar{V}_{qn}^{(l)}\}, \quad l = 1, \dots, L,$$

$$\bar{V}_{qn}^{(l)} = \begin{cases} 0 & n \in \theta_{l-1} \text{ and } q = q_{l-1}, \\ \bar{V}_{qn}^{(l-1)} & \text{otherwise} \end{cases}$$

The statistical component of the error can be estimated as $\delta_s^2 \approx R/(N \cdot SNR)$ [7].

4.4. Diversity combining and decoding

The estimates $\hat{H}_l(\omega)$ are used for diversity combining. The spectral sequence $Y_l(k) = \bar{Z}_l(k)\hat{H}_l^*(\omega_k)M_2(k)$ corresponds to the

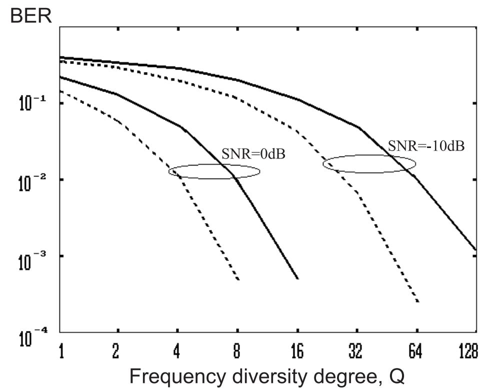

Fig. 1. *BER performance. Experiment 1 (—), calculation (- - -).*

matched filtration of the signal component propagated over the l-th macro-ray. The combining of Q frequency diversity signals is performed as

$$w_l(m) = \sum_{i=0}^{Q-1} Re\{Y_l(m + iN/Q)\}, \;\; m = 0, \ldots, N/Q - 1,$$

where m is the index of a data bit within an OFDM symbol and $Re\{\cdot\}$ denotes the real part of a complex-valued number. The multipath-Doppler combining is performed by

$$w(m) = \sum_{l=1}^{L} w_l(m). \tag{10}$$

Finally, the estimate of the data bit d_m is $\hat{d}_m = sign\{w(m)\}$.

5. EXPERIMENTAL RESULTS

Five experiments were carried out under different propagation conditions. Experiments 1-4 were performed with transmitting and receiving drifting ships; each communication session with signal parameters $T_s = 4$ sec, $f_c = 768$ Hz and $F = 256$ Hz lasted about 30 min. In Experiment 5 a receiving ship was drifting, but a transmitting ship moved with a speed of 5 m/s; the duration of the communication session was 6.4 min; the signal parameters were $T_s = 1$ sec, $f_c = 3072$ Hz and $F = 1024$ Hz. In all the experiments an omnidirectional transducer was used for transmission of the acoustic signals.

Experiment 1 was performed in the Baltic sea at a distance of 20 km with both a transducer and receiving hydrophone placed at a depth of 50 m. The channel impulse response contains a continuous group of rays with a maximum delay of 125 ms. More detailed description of this experiment can be found in [8]. Fig.1 shows for this experiment the BER versus the frequency diversity degree Q. In this figure, results of BER calculation according to [9]

$$P_Q = \frac{1}{2}\left\{1 - \left[\frac{SNR}{SNR+1}\right]^{\frac{1}{2}} \left[1 + \sum_{k=1}^{Q-1} \frac{(2k-1)!!}{k!2^k(SNR+1)^k}\right]\right\}$$

are also presented. This formula applies to independent Rayleigh fading in diversity branches with equal average SNRs. However,

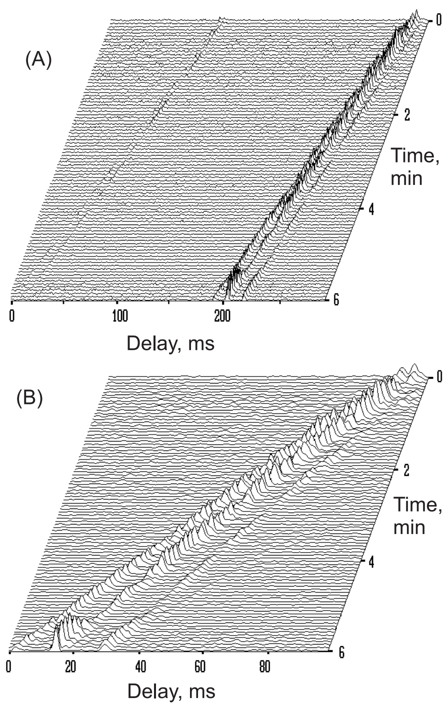

Fig. 2. *Channel impulse responses. Experiment 5.*

comparison of experimental and calculated BER demonstrates different performance; this is attributed to both considerable correlation between frequency diversity channels (the interval of correlation is about 8 Hz) and a large range of average SNR across the frequency channels (the average SNR versus frequency varies more than 10 dB).

Experiments 2, 3 and 4 were performed in the Indian Ocean at distances of 3 km, 90 km and 525 km, respectively, with transmission at a depth of 200 m. In Experiment 2, an omnidirectional receiving hydrophone was used at a depth of 500 m; the channel impulse response contains two macro-rays (direct and reflected from the surface) with a delay of 22 ms. In Experiment 3, the signal was received by a directional antenna at a depth of 180 m; the propagation conditions correspond to a second shadow zone; the channel impulse response contains two intensive macro-rays with a delay of 50 ms and two weaker rays with delays of 750 ms and 900 ms with respect to the first ray. In Experiment 4, the signal was received by a directional antenna at a depth of 180 m; the channel impulse response contains two intensive rays with a delay of 16 ms.

Experiment 5 was carried out in the Pacific Ocean at distances of 50-52 km. Fig.2 depicts channel impulse responses measured during the communication session; there are two groups of macro-rays with the delay of about 200 ms. The more intensive group is depicted in Fig.2B; the variation in relative delays during the communication session can be seen. Fig.3 shows the channel scattering function averaged over a time interval of 8 sec; wide Doppler scattering caused by varying channel parameters can be seen. Fig.4 shows fluctuations of the Doppler parameter for the most inten-

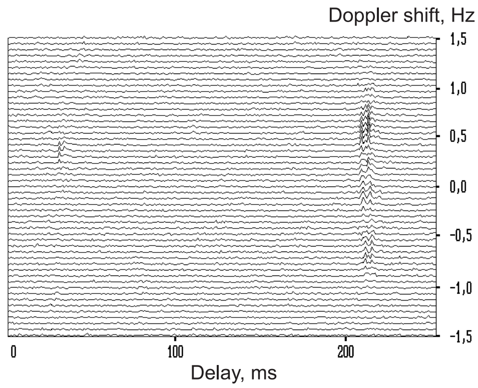

Fig. 3. *Channel scattering function. Experiment 5.*

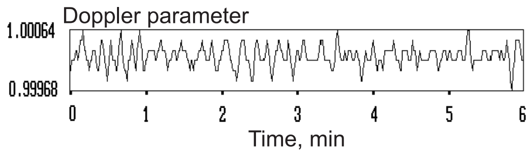

Fig. 4. *Fluctuations of the Doppler parameter. Experiment 5.*

sive macro-ray; the spectrum of these fluctuations demonstrates high spectral components with periods of 5-16 sec corresponding to fluctuations of the sea surface. Fig.5 shows the BER versus Q in these experiments (for SNR=0 dB). It can be seen that the BER performance varies in a small range (less than a factor of 2 for the parameter Q) for different propagation scenarios. This shows that the channel model (2) is in good accordance with the underwater acoustic propagation, and the proposed algorithm of joint multipath-Doppler diversity of OFDM signals allows us to realise advantages given by this channel model.

6. CONCLUSIONS

We have studied a receiver of OFDM signals with frequency diversity of transmitted data. The proposed demodulation algorithm is based on coherent weighted addition of frequency, delay and

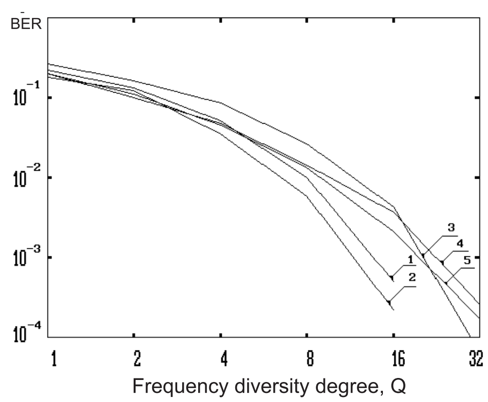

Fig. 5. *BER performance. Experiments 1-5.*

Doppler shifted signal copies. Experiments carried out in different propagation scenarios have demonstrated that the error rate depends basically on signal-to-noise ratio and is practically independent of other channel characteristics. The algorithm can also be used for multipath-Doppler diversity in mobile radio communications systems operating in fast fading channels.

7. REFERENCES

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