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Experimental research of underwater acoustic long-range transmission of high-rate data

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Abstract: A number of data transmission experiments were carried out in deep ocean to demonstrate advantages of diversity reception and of application of families of pseudorandom waveforms for long-range data transmission over underwater acoustic channel.

1 - Introduction

At long range, the underwater acoustic propagation is characterized by multipath, dispersion and fading effects. The effectiveness of acoustic communication systems are mainly limited by these phenomena [1]. To increase the effectiveness frequency, spatial and temporal diversities and their combination are used for fading channels [2-5]. This work is devoted to delay diversity (multipath propagation) and spatial diversity. To increase the data rate over dispersive channel it's necessary to use families of waveform codings [6]. We consider here the experimental research results of the acoustic spread spectrum communication system with a large family of waveforms.

2 - Transmission signals

For the data transmission we use waveforms defined by

$$s_m(t) = A \sum_{n=0}^{N-1} \cos \left[2\pi \left(f_c - \frac{F}{2} + \frac{n}{T} \right) t + \varphi_m(n) \right], \quad t \in [0, T], \quad m=1, \overline{M}, \quad (1)$$

where A is an amplitude factor, m is a serial number of the waveform, M is a size of the family, $N=1024$ is a number of harmonic components, f_c is the carrier frequency, T is a duration and $F=N/T$ is a bandwidth of waveform. The family of waveforms is determinated by phase shift keying $\varphi_m(n)$:

$$\sqrt{2} \exp\{j\varphi_m(n)\} = a_m(n) + jc(n), \quad (2)$$

where $a_m(n)$ and $c(n)$ are binary pseudorandom sequences. The first one is used for data transmission, and the second - to estimate the channel scattering function. Two families of waveforms were used in our experiments. The first one is defined by

$$a_m(n) = M(n)W_m^N(n), \quad m=1, \dots, N, \quad (3)$$

where $M(n)$ is M -sequence, $W_m^N(n)$ is m -th Walsh-function of length N . From sequences $a_m(n)$ we select $M=N/2$ sequences, which ensure minimal peaks of the cross correlations. In other family the sequences are formed by the rule:

$$a_m(n) = M(n) W_{m_i}^{N/8}(k), \quad m_i = 1, \dots, N/8, \quad n = 8k + i, \quad k = 0, \dots, N/8 - 1, \quad i = 0, \dots, 7. \quad (4)$$

The data rate providing by the first family is $9/T$ b/s, by the second - $56/T$ b/s.

The amplitude distribution of transmission signal is approximately Gaussian, and the power spectrum is roughly rectangular for $f \in [f_c - F/2, f_c + F/2]$. The ambiguous function is close to δ - function at the plane delay - Doppler shift ($\Delta\tau = 1/F$ and $\Delta f = 1/T$).

3 - Channel model and receiver structure

Let $s(t)$ be the transmitted signal, $x(t)$ received signal, and $b(t)$ an additive noise. A multipath model is

$$x(t) = \sum_{l=0}^{L-1} A_l(t) s[d_l(t)t - \tau_l(t)] \exp(j\theta_l(t)) + b(t). \quad (5)$$

The channel consists of L paths of strengths $A_l(t)$, delays $\tau_l(t)$ and phases $\theta_l(t)$. Parameter $d_l(t)$ characterises time scale defined by Doppler effect. We assume that the channel parameters variance is insignificant on time interval T . According to (5) it is assumed that time-delayed components arriving over different paths are not identically perturbed by Doppler effect. This situation is shown in Fig.1.

Receiver consists of synchronizer and demodulator. Using FFT, synchronizer calculate ambiguous function for synchro- and received signals (as in Fig.1). This function is used to estimate magnitudes A_l , delays τ_l and Doppler parameters d_l . Demodulator use FFT and Fast Walsh Transformation to calculate incoherent cross-correlations of received signal replica with all informative signals for each diversity path. Then it executes combining weighted defined by magnitudes of the replicas, the largest cross-correlation indicates the received waveform.

4 - Experimental Results

During the experiments we estimated effectiveness of the diversity reception under various conditions of acoustic propagation. Analysis of channel parameters estimations allows to determine spread of the channel. Transmitted signal of length about $500 \cdot T$ was generated by computer and then was tape-recorded. During the experiments the signal was emitted through an amplifier-omnidirectional transducer combination into the water. Received signals were processed in real time and simultaneously tape-recorded for further processing.

Let's consider the results of some experiments, which were carried out in deep ocean by two drift ships.

1. Indian Ocean, 5200 m depth, distance between the ships 694km, axis of sound channel is at a depth 1100m. At a depth 200m the signals defined by (3) were transmitted in the 640...896 Hz band, the data rate was 2.25 b/s. There were two several propagation rays, which were selected by receiving vertical array at a depth 545m and then

independently processed. The single-ray fading is well described by internal waves model with the Garret-Mank spectrum [7]. The received signal-to-noise ration (SNR) varies in the range (≤ 0 dB)...+14dB. Fig.2 shows the channel impulse responses for the single ray.

We use 1...10 delay diversity paths. For the first selected ray (Fig.2) a number of errors is 3.2%, 1.4%, 1.0%, 0.6%, 0.0%,..., 0.0%, respectively. For the second ray a number of errors is 5.8%, 3.2%, 0.6%, 0.0%,..., 0.0%, respectively. For signal receiving by omnidirectional hydrophone a number of errors is 43% in case one diversity path (maximum output selection), and 27% in case five diversity paths.

2. Under the same conditions at distance 525km and depth 512m signal was received by omnidirectional hydrophone. There were four independently fluctuating rays (Fig.3). SNR was not greater than 0dB. Maximum output selection gave 8.2% errors, ten diversity paths gave 1.8% errors. Processing of a signal received by directional array at the 180m depth for 4...10 diversity paths yields no errors.

3. Atlantic Ocean, 3800m depth, distance 88km, axis of sound channel is at a depth 550m. At a depth 200m the signals defined by (4) were transmitted in the 1030...1442 Hz band, the data rate was 23 b/s. Two hydrophones received the signals at a 100m and 140m depths simultaneously. The typical channel impulse response is shown in Fig.4.

During the experiment SNR varied in the range -1dB...+6dB. The results concerning the joint processing both signals are present in the first line of table 1. The distance of third hydrophone from the ship was 400m, the depth was 120m, that allowed to increase SNR up to: +4dB...+14dB. The results concerning the third hydrophone are present in the second line of table 1. The number of errors in both cases was quite the same for the same number of diversity paths. It's shown larger effectiveness of joint delay and spatial diversity in comparison with simple delay diversity.

4. Pacific Ocean, 5200m depth, distance 112km, axis of sound channel is at a depth 800m. At a depth 250m the signals defined by (4) were transmitted in the 3250...4550 Hz band, the data rate was 71 b/s. The signal was received by omnidirectional hydrophone at a 250m depth, SNR varies in the range +5dB...+17dB. Maximum output selection gave 39% of errors. In case 5 diversity paths we obtained 2% of errors.

5. Pacific Ocean, 5150m depth, axis of sound channel is at a depth 850m. At range of 54...57km towing transducer (the depth 250m, the velocity 5m/s) transmitted data (4) in the 2460...3584 Hz band, the data rate was 56 b/s. The signal was received by omnidirectional hydrophone at a 145m depth, SNR varies in the range +4dB...+21dB. Signal processing in one Doppler channel didn't allow to obtain less than 8.5% of errors. Joint processing 7 Doppler channels for 10 delay diversity paths allowed to obtain error-free communication.

5 - Conclusions

We illustrate here the advantages of diversity reception for long-range data transmission by families of pseudorandom waveforms. The effectiveness of delay diversity increases with number of diversity paths until all powerful time-delayed replicas were processed. It is important to note the low effectiveness of maximum output selection for delay diversity. Joint delay and spatial diversity is more effective than simple delay diversity for the same number of the diversity paths. Application of directional arrays significantly improves reliability of considerable diversity reception.

Fig. 1. Estimation of the channel scattering function, range 55 kn, velocity of transmitting transducer 5 m/s.

Fig. 2. The impulse responses of channel, range 694 kn.

Fig. 3. The impulse responses of channel, range 525 kn.

Fig. 4. The impulse response of channel, range 80 kn.

Table I. Number of errors.

Number of diversity paths	1	2	5	10	15
Delay and spatial diversity	14%	7.1%	1.8%	0.37%	0.37%
Delay diversity	14%	4.4%	0.86%	0.43%	0.43%

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