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Experimental demonstration of single carrier underwater acoustic communication using a vector sensor

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ABSTRACT

Vector sensors could simultaneously collect not only pressure but also velocity signals and there will be a valuable gain when combining these two kinds of signals properly. This paper studies single carrier underwater acoustic (UWA) communication using a vector sensor. In a recent field experiment, acoustic communication transmissions were carried out over a 1 km range in shallow water at Songhua River, Heilongjiang province, China. The same coded signal was transmitted when the vector sensor was deployed to depth of 1 m, 1.5 m, 2 m, and 2.5 m respectively. Decoding results, that nearly error-free performance at four depths, show the robustness of UWA communications using a single vector sensor in a highly refractive environment. The four received signals are also combined together to asynchronously realize a vertical array processing using passive time reversal based on the spatial and temporal diversity, achieving a maximum gain about 8.02 dB compared with a single sensor processing.

1. Introduction

Ocean sampling is now playing a more and more important role in the field of marine environment and global climate monitoring. While data from satellites and airplanes can provide with some useful information, it does not present information far below the ocean surface [1]. Variable undersea observation equipments such as autonomous underwater vehicles (AUVs) have emerged over the last decade to further understand the internal changes of ocean. Undersea observation equipments rely on high data rate UWA communications to transmit huge amount of data to the base station in real-time.

However, the UWA channel is generally recognized as one of the most difficult communication channels today [2,3]. It has very severe delay spreads which could be on the order of 100 ms in shallow water and varies fast both in spatial and temporal domain. The useful bandwidth of UWA channel is very limited due to large transmission loss related to the carrier frequency. All these factors make it very difficult to communicate in UWA environment, especially for high data rate communications.

Orthogonal Frequency Division Multiplexing (OFDM) has been a hot topic in high data rate UWA communications for its good performance in anti inter symbol interference (ISI) and bandwidth efficiency. Researchers all over the world have conducted a lot of simulations and experiments based on OFDM, yielding promising results [4–7]. However, there are also some known drawbacks. OFDM signal has higher peak-to-average power ratio (PAPR) which makes it difficult to transmit using transducers. As subcarriers are densely spaced in frequency domain, Doppler shifts due to relative motion between the source and the receiver will damage orthogonality of subcarriers, causing severe inter carrier interference (ICI).

Single carrier communication outperforms OFDM in terms of signal PAPR and sensitivity to Doppler shifts. It has been widely used in UWA communications since Stojanovic et al. [8] introduced decision feedback equalizer (DFE) embedded with phase lock loop (PLL) into this scheme, solving the problem of phase tracking in 1994. The computation complexity of DFE in single carrier communications is very large as the taps should span the whole severe multipath spread. Frequency domain equalization [9–11] which adopts FFT and IFFT to realize channel equalization instead of DFE has been proposed in order to decrease the system complexity. In most cases, using only a single sensor is not enough to recover transmitted signals for long range communications. So a vertical array with multiple sensors is always used in single carrier communications. Song et al. [12–14] studied time reversal DFE which is proved to have a similar performance with multichannel DFE [15,16]. Both methods exploit spatial diversity achieved by a vertical array to get nearly ideal results.

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The motivation of this paper is to investigate UWA communications using a single vector sensor. Vector sensors could collect not only pressure signals but also velocity signals and there will be a valuable gain when combining these two kinds of signals properly. To accomplish this objective, a field experiment (SHJ14) was conducted in Songhua river, Heilongjiang province, China in November 2014.

Section 2 reviews the signal processing method using a vector sensor and time reversal, proposes the scheme in this paper. Section 3 describes the experiment environment. Section 4 presents decoding results using vector sensor. Section 5 is a brief summary.

2. Single carrier communication using a vector sensor

2.1. Signal model of vector sensor

Vector sensor is made up of a traditional pressure sensor which has no directivity and three velocity sensors. It could collect not only pressure but also orthogonal velocity information in the underwater acoustic environment. So it has more inputs compared with pressure sensors. Denote $s(t) = [p(t) \quad v_x(t) \quad v_y(t) \quad v_z(t)]^T$ as the output signals of vector sensor, where $p(t)$ is the pressure signal and $v_x(t)$, $v_y(t)$, $v_z(t)$ are three velocity signals. Acoustic represents as standing wave in the vertical direction in ocean waveguide. So only $p(t)$, $v_x(t)$, $v_y(t)$ can be used in underwater acoustic communications. Consider a two-dimensional condition, received signals of vector sensor can be described as

$$\begin{cases} p(t) = x(t) \\ v_x(t) = x(t)\cos\theta \\ v_y(t) = x(t)\sin\theta \end{cases} \tag{1}$$

where θ is the horizontal azimuth of acoustic arrivals and $\theta \in [0, 2\pi]$ Dipole directivity of vector sensors can be electronic rotated. Donate $v_c(t)$ and $v_s(t)$ as the combined directivity after electronic rotated, then

$$\begin{cases} v_c(t) = v_x(t)\cos\varphi + v_y(t)\sin\varphi = x(t)\cos(\theta-\varphi) \\ v_s(t) = v_x(t)\sin\varphi + v_y(t)\cos\varphi = x(t)\sin(\theta-\varphi) \end{cases} \tag{2}$$

where φ is the guide bearing. A linear combination (i.e. $p + a \cdot v_c$) of $p(t)$ and $v_c(t)$ is usually used in underwater acoustic communication aiming to get more processing gain. It is necessary to discuss the processing gain of $p + a \cdot v_c$ here. Suppose signal power and noise power in $p(t)$ are σ_s^2 and σ_n^2 respectively. Signal power and noise power in $v_c(t)$ will be σ_s^2 and $\sigma_n^2/2$. So the SNR of $p + a \cdot v_c$ can be described as

$$(S/N)_{pv} = \frac{(1+a)^2}{1+a^2/2} \cdot \frac{\sigma_s^2}{\sigma_n^2} \tag{3}$$

The SNR will reach a maximum value when $a = 2$. So in the following processing of experimental data $p + 2 \cdot v_c$ will be deployed.

2.2. Single carrier communication scheme

Fig. 1(a) depicts the single carrier communication scheme using a single vector sensor. It mainly consists of two parts: vector signal processing and DFE. Vector sensor processing could get input gain through combining $p(t)$ and $v_c(t)$; DFE is used to compress multipath spread. Fig. 1(b) is the scheme when multiple sensors could be used. Input signals are firstly combined at every channel and then time reversal mirror (TRM) is used to compress the multipath, following a single channel DFE to remove residual ISI. A key part in Fig. 1 is the source bearing estimator. Active average acoustic intensity (AAAI) [17] is used in this paper to estimate source bearing.

Fig. 2 shows the structure diagram of AAAI. Suppose the local reference signal is $r(t)$, synchronous signals extracted in $v_x(t)$ and $v_y(t)$ will be matched filter with $r(t)$, and then select the maximum value.

The output of AAAI after peak selector

$$\begin{cases} \bar{I}_x = \max[r(t)v_x(t-\tau)] = \max[C_{v_x,r}(\tau)] = A_s\cos\theta + \Delta_x \\ \bar{I}_y = \max[r(t)v_y(t-\tau)] = \max[C_{v_y,r}(\tau)] = A_s\sin\theta + \Delta_y \end{cases} \tag{4}$$

where A_s is the correlation peak; Δ_x and Δ_y are small interference. So the estimated bearing is

$$\hat{\theta} = \arctan\frac{\bar{I}_x}{\bar{I}_y} \tag{5}$$

3. SHJ14 experiment

SHJ14 based on single carrier underwater acoustic communication [12] was conducted at Songhua river, Heilongjiang province, China in November 2014. The communication sequences are modulated using QPSK. The transmitted waveform is pulse shaped using a raised-cosine filter with a roll-off factor 0.7. The center frequency is 12 kHz, the symbol rate is 2 k symbols/s, and all signals are sampled at 96 kHz. 26,000 bits data were transmitted during this experiment and the first 1000 bits were used as training ($N_T = 500$).

The schematic of SHJ14 is shown in Fig. 3. The experiment involves one transducer, denoted by T whose source level was 186 dB re 1 μP_a at 1 m, having a bandwidth of 8–20 kHz. The transducer was deployed to 1.5 m depth. A vector sensor, 1000 m away from the source, was deployed off the receiving boat which was always moored during this experiment. Note that the vector sensor was rigidly connected to the receiving boat through a steel pipe whose diameter was about 10 cm.

The vector sensor was orderly deployed to point A, B, C, and D respectively. The same signal was transmitted at every depth and received signals were denoted by VS01, VS02, VS03, and VS04 in sequence. These collected signals will be used to demonstrate the decoding advantages of a single vector sensor processing.

Fractionally spaced equalizers (two samples per symbol) were used for feed forward filters, and the number of feed forward (FF) and feedback (FB) filter taps were both 20. The proportional and integral phase tracking constants for the PLL were P_1 = 0.0001 and P_2 = 0.00001, respectively. The recursive least square (RLS) algorithm was employed to adaptively update the DFE equalizer coefficients with a forgetting factor $\lambda = 0.9965$.

4. Performance analysis

In addition to transmitting the coded signal, linear frequency modulated (LFM) chirps, 50 ms in duration, and 10–14 kHz in frequency were also sent as sync signals. The chirp sequences were used to detect channel impulse response (CIR) from the source to vector sensor at different depths. The received signals are firstly match filtered by the local sync signal, that LFM chirps. Fig. 4 shows the output after match filtering the received signals VS01, VS02, VS03, and VS04 respectively.

From Fig. 4 the following conclusions can be draw: (1) the multipath spread is less than 5 ms, not very severe at communication range 1000 m; (2) the multipath structure is not clear and acoustic arrivals from the source mixed together, indicating that the experimental environment is highly refractive. The angles estimated by AAAI method for VS01, VS02, VS03, and VS04 are 35°, 37°, 34°, and 33° respectively. The differences between estimated angles