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Doppler Compensated Front – End Receiver Design for Underwater Acoustic Channels Using Mimo-Ofdm

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Abstract
Over the past three decades underwater acoustic communications has grown in a spectaculous manner. Continued research over the years has resulted in improved performance and robustness as compared to the initial single-carrier communication systems. Multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) has emerged as a promising modulation scheme for underwater acoustic (UWA) communications. Multiple-input multiple-output (MIMO) techniques have been actively pursued in UWA communications recently to increase the system performance over the bandwidth-limited channels. However, UWA channels are far more challenging than their radio counterparts. Due to their limited bandwidth, even though UWA channels are wideband in nature due to the small ratio of the carrier frequency to the signal bandwidth, which introduces Doppler shift that destroys the orthogonality among OFDM subcarriers. To mitigate the effect of Doppler shifts in OFDM transmissions over UWA channels, Doppler compensation is done through multiple resampling at front-end receivers. In this paper, we treat the channel as having a common Doppler scaling factor on all propagation paths, and propose linear minimum mean square error (LMMSE) estimation algorithm. Comparing with the conventional MMSE, this algorithm has the advantage of low complexity. The results suggest that MIMO-OFDM is an appealing solution for Doppler compensations for data transmissions over underwater acoustic channels.
Index Terms—UWA channels, OFDM, MIMO, Doppler shift, LMMSE.

I. INTRODUCTION

The abundance of water on earth distinguishes our Blue planet from others in the solar system. Underwater exploration activities are mainly hampered by the lack of efficient means of real-time communications below water. Although wire line systems through deployment of fiber optical links have been used to provide real-time communication in some underwater applications, their high cost and operational disadvantages become restrictive; in such a case wireless communication is a promising alternative. In recent years, UWA communications have received much consideration as their applications have begun to shift from military toward commercial. UWA channels are generally recognized as one of the most difficult communication media in use today. Acoustic propagation is best supported at low frequencies, and the bandwidth available for communication is extremely limited. Digital communications through UWA channels differ substantially from those in other media, due to severe signal degradations caused by multipath propagation and high temporal and spatial variability of the channel conditions.

Acoustic propagation is characterized mainly by three major factors: attenuation that depends on the signal frequency, multipath propagation, and nominal low speed of sound (1500 m/s).Transmission schemes based on OFDM have recently emerged as an attractive solution for UWA communications [2]–[6]. OFDM modulation was proposed in the 1960s [2], and it was suggested for wireless applications in the 1980s [3]. OFDM is a special form of multicarrier modulation technique which modulates the data over a large number of carriers that are mutually orthogonal.

Acoustic channels develop efficient, reliable and high speed transmission solutions tailored for challenging the diverse requirements of underwater applications. In comparison to RF and optical waves, acoustic wave transmission is more practical to use in underwater with its support for long range transmission due to relative propagation characteristics of sound waves. OFDM in the UWA channel experiences non negligible Doppler shift which distinguishes an acoustic channel from a radio channel. Since the speed of sound is very low compared to electromagnetic waves, the distortion due to Doppler can be quite severe for acoustic signals.

In this paper, we focus on a major challenge, namely the OFDM transmission used with UWA channels for Doppler shift compensation using front-end receiver structures with multiple resampling and LMMSE algorithm.

II. SYSTEM MODEL

OFDM is a promising modulation scheme over frequency selective channels. In an OFDM system, the usable bandwidth is divided into N spectrally equispaced subcarriers [12]. Thus, N transmitted signals are modulated onto each subcarrier independently. An OFDM signal consists of N subcarriers with frequency spacing Δf. The signal waveforms on the subcarriers are orthogonal to each other within a period of $T_f \equiv 1/\Delta f$. To avoid interblock interference (IBI), the OFDM symbol block is extended by a cyclic prefix (CP), which is also called the guard interval with length T_g. Hence, the complete OFDM block duration is $T = T_f + T_g$. If the guard interval length T_g is larger than the maximum channel delay spread, the interference from previous OFDM symbol blocks appears within the guard interval only. At the receiver, the signal samples in the guard interval are discarded.

Therefore, IBI is completely eliminated, and the orthogonality of subcarriers can be retrieved at the receiver. Pilot symbols are added in order to avoid loss of data, by transmitting the data in blocks. The data bits provided from the source are converted from serial to parallel to form parallel data after modulation. The modulated data is inserted with pilots form N subcarriers and each subcarrier consists of data symbol $X(k)$, where k represents the subcarrier index. Where $f_k = f_0 + k/T$ is the frequency of the kth subcarrier, $1/T$ is the spacing between consecutive subcarriers, and $T_g < T$ is the duration of the CP [2]. After the inverse fast Fourier transform (IFFT), the time domain OFDM signal can be expressed as,

$$x(n) = \sum_{k=0}^{N-1} X(k)\, exp\left(\frac{j2\pi kn}{N}\right) \quad 0 \le n \le N-1 \quad (1)$$

where, n is the time domain sample index of an OFDM signal. After adding CP, to the transmitted signal $x_g(n)$ is then sent through the channel. The received signal can be represented by,

$$y_g(n) = x_g(n) \otimes h(n) + w(n) \quad 0 \le n \le N-1 \quad (2)$$

where, $w(n)$ is independent and identically distributed additive white Gaussian noise (AWGN) sample in time domain and $h(n)$ is the discrete time channel impulse response. At the receiver side, after removing the CP, the received samples are sent to a FFT block to demultiplex the multicarrier signals. The kth subcarrier output in frequency domain can be represented by,

$$Y(k) = \frac{1}{N}\sum_{n=0}^{N-1} y(n) exp\frac{-j2\pi kn}{N}$$
$$= X(k)H(k) + W(k) \quad 0 \le k \le N-1 \quad (3)$$

where, $W(k)$ is represented as $w(n)$ in frequency domain and $H(k)$ is the channel frequency response. The basic block diagram of the OFDM system is shown in Fig.1.In practice, the CP is long enough, in order to maintain the orthogonality of the subcarriers.

III. SYSTEM DESIGN AND DOPPLER EFFECT

Most early UWA communication systems used incoherent modulation methods for reasons of simplicity and reliability. Through the 1980s phase-coherent communication was used almost exclusively for deep-water vertical links, but in the early 1990s phase coherent communication in multipath channels began to attract attention.The coded bits are mapped into information symbols using Quadrature Phase Shift Keying (QPSK) modulation.

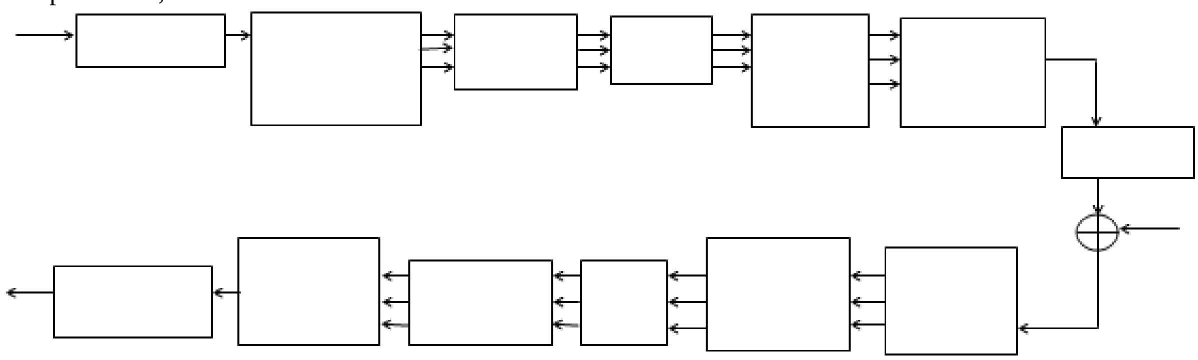

Fig.1. Block Diagram of OFDM system

A 16-Quadrature Amplitude Modulation (QAM) format is used, and the performance is aided by an LMMSE algorithm suffices to reduce the bit error rate from 10^{-4} to 10^{-6} on this channel. In order to increase the system performance and throughput a LMMSE is proposed. MMSE is simple in implementation, but faces singularity problem. To overcome this problem, singular value decomposition method can be used but it increases computational complexity. LMMSE estimation is used to estimate path gain, delay and Doppler scaling factor. Front –

end receivers includes multiple resampling (MR) branches, for Doppler scaling factor associated with different users or different propagation paths of the same user is shown in Figure 2.

For the Doppler spread case, linear detection based on MMSE optimization is adopted. Preferably to assess the performance of the proposed receivers, compare the results with those obtained by a standard receiver, for which only a single resampling (SR) branch is employed. CP is maintained sufficiently long enough to prevent IBI. A good understanding of the channel is important in the design and simulation of a communication system.Relative motion between a source and a receiver results in a Doppler scaled communication signal. To handle the time-scale change, a resampling methodology proved effective in underwater communications [6], [7].In this paper, for Doppler compensation multiple resampling method is approached. As the transmitter and receiver move relative to each other, the distance between them changes, and so does the signal delay.
As a consequence, the leading edge of a transmitted signal may experience one delay, while the trailing edge will experience another. Non-negligible motion induced Doppler spreading thus emerges as major factor that distinguishes an acoustic channel from the mobile radio channel. The approach that has demonstrated successful performance in single carrier broadband acoustic systems is that of coupled equalization and synchronization [10]. Motion of the transmitter or receiver contributes additionally to the changes in channel response which causes frequency shifting as well as additional frequency spreading. The magnitude of the Doppler scaling factor is proportional to the ratio $a = v/c$ of the relative transmitter /receiver velocity to the speed of sound. In other words, there is always some motion present in the system, and a communication system has to be designed taking this fact into account. Although the UWA channels are generally confined to low data rates (as compared to the radio channels), the encountered channel distortions require complex receiver structures, resulting in high computational load.

Consequently, reducing the receiver complexity to enable efficient real-time implementation has been a focus of many recent studies. Two commonly used kinds of algorithms are based on the LMS and the RLS principles [4]. In a majority of recent studies, the LMS-based algorithms are considered an only alternative due to their low computational complexity (linear in the number of coefficients$N$) [4]. In addition, the conventional MMSE is very complex. To overcome this problem, self-optimized LMMSE algorithms is used [10].An efficient implementation of OFDM [with or without a (CP)] can be obtained by a block wise IFFT of the input signal.

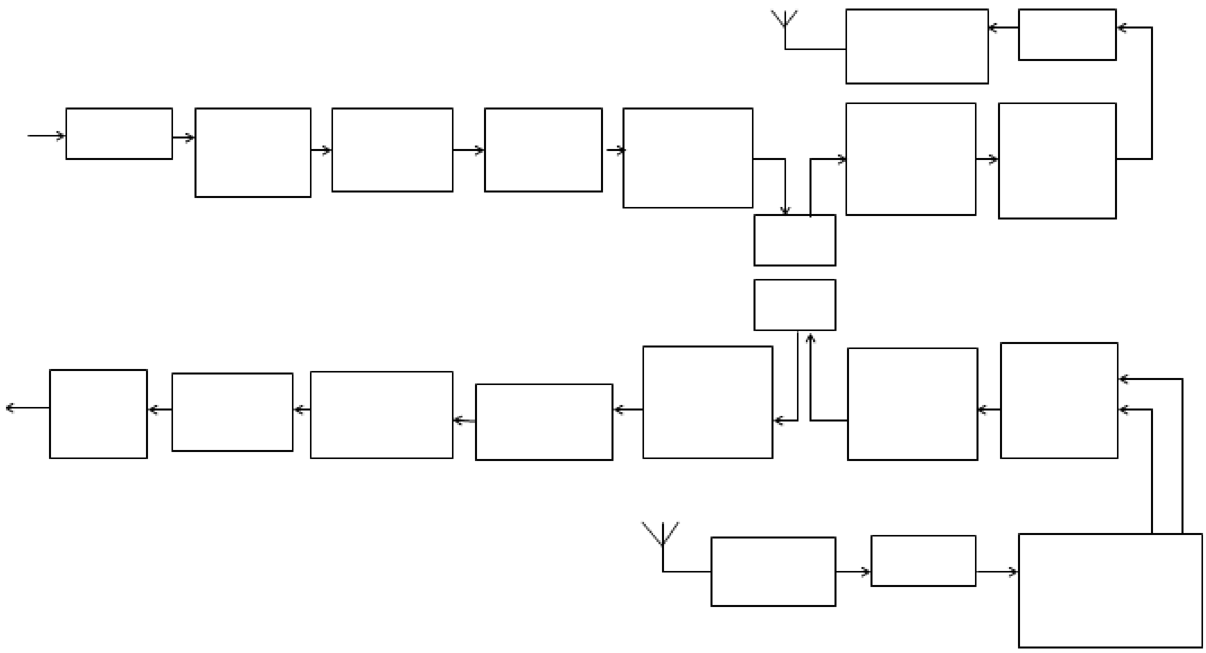

Fig.2. Block diagram of OFDM-MIMO transceiver

IV. NUMERICAL RESULTS

In this paper, in order to show simulation results for the proposed MIMO-OFDM system used in UWA communications, the following parameters are considered as shown in Table 1.

Data Samples	9600 samples
Cyclic Prefix Insertion	100 samples
Pilot data	52 sample
Modulation	QAM
Algorithm	LMMSE
Parameters	SNR,BER

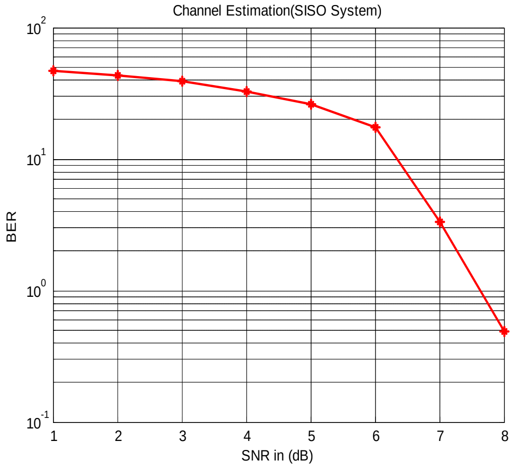

Fig.3. Channel Estimation (SISO) system

From Fig.3 simulation output, the channel parameters of SISO system is shown with respect to Signal to noise ratio (SNR).The system produces SNR around 8dB which can be enhanced in MIMO system.

In Fig.4 simulation output, the OFDM system is employed along with QPSK. The system produces enhanced results compared with the SISO system. BER is decreased 10^{-1} to 10^{-4} and a considerable increase in SNR to 12dB.

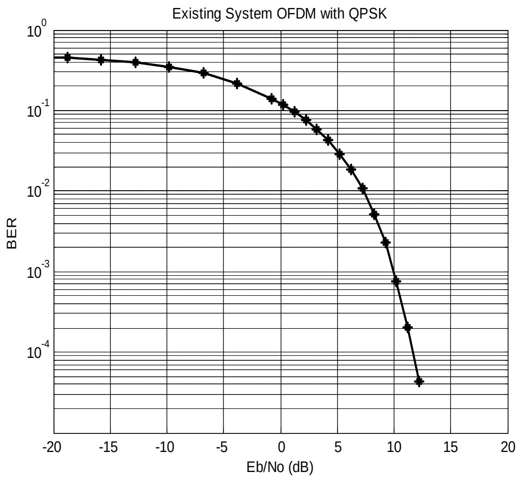

Fig.4. OFDM system with QPSK

In Fig.5 simulation output, LMMSE algorithm is applied to a MIMO-OFDM system. Preferable results are produced compared to the conventional outputs; BER is reduced from 10^{-4} to 10^{-6} with an increase in SNR from 8dB to 14dB.Thus MIMO systems under the implementation of LMMSE increases the system performance.

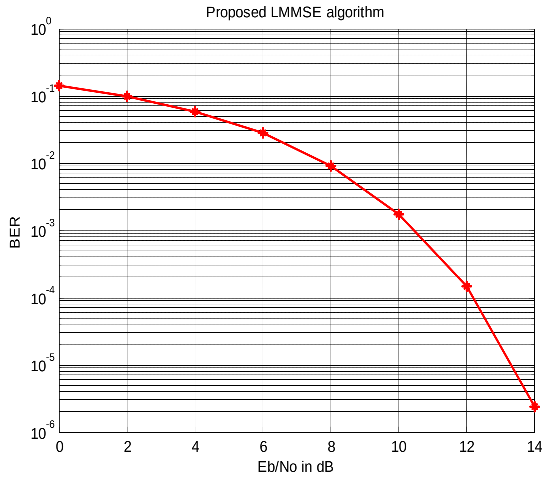

Fig.5. Proposed LMMSE algorithm

From Fig.6 simulation graph, it shows the difference in performance of the system according to conventional MMSE and LMMSE algorithms. BER is considerably reduced in case of LMMSE algorithm.

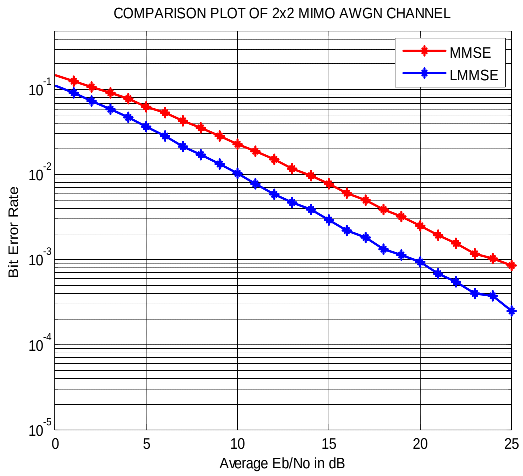

Fig.6. Comparison of MMSE and LMMSE

In an MIMO-OFDM system implemented using resampling, the system performance is increased sufficiently. Fig.7 output shows the difference between with and without resampling.

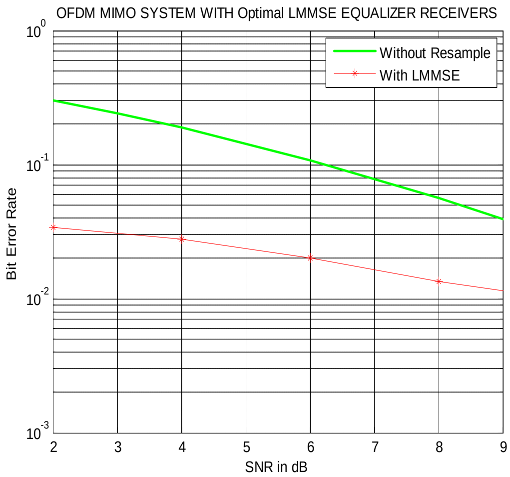

Fig.7. OFDM-MIMO system with & without resampling

In Fig.8 simulation output, it plots the different values for varying values of CFO in the system. Reduced CFO implies better system throughput, for small values of CFO the BER is reduced or negligible. The graph plots five different values of CFO.

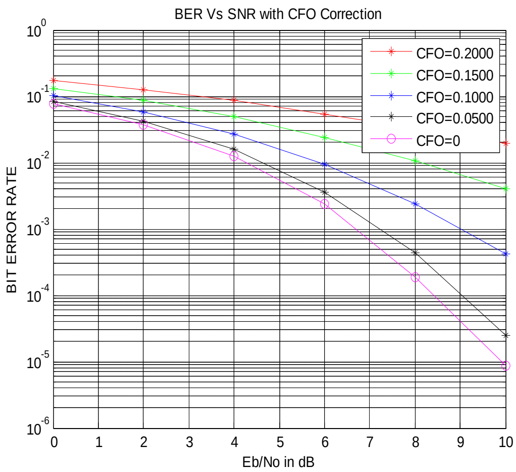

Fig.8. CFO Correction in system

V. CONCLUSION AND FUTURE RESEARCH

In this paper, an attempt is made to summarize the recent advances in the field of MIMO-OFDM systems along with UWA communications. Using a family of front-end receiver structures combined along with MR for Doppler compensation and a novel LMMSE channel estimation scheme is proposed and its performance is numerically confirmed for the OFDM system defined in the IEEE 802.11a standard. Preferable numerical results are obtained with LMMSE algorithm compared to conventional MMSE algorithm and this scheme can reduce the computational burden. Therefore, it is rather attractive for practical application in MIMO-OFDM based communication systems.

Future research canbe focused on the development of more sophisticated processing algorithms which will enable efficient and reliable data transmission in varying system configurations and channel conditions. In future, the system can be extended using water filling algorithm for power allocation in the channel which in turn reduces ICI which occurs due to carrier frequency offset (CFO). In order to further enhance the MIMO-OFDM system, a joint Normalized mean square error (NMSE) and Maximum likelihood (ML) based channel estimation can be carried out.

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