A Survey on DSP Implementation of OFDM UW Acoustics Modem

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Abstract *-Recently, there has been a growing interest in monitoring aqueous environments (including oceans, rivers, lakes, ponds, and reservoirs, etc.) for scientific exploration, commercial exploitation, and protection from attacks. The ideal tool for this type of extensive monitoring is a networked underwater wireless sensor distributed system, referred to as the Underwater Wireless Sensor Network (UWSN). Significant progress has been made on the use of multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) for high data rate underwater acoustic communications. We have demonstrated OFDM transmission first in air, and then in water by analyzing channel estimation techniques and channel impulse response*.

Keywords- OFDM, multicarrier transmission, UWSN, underwater acoustic communication

INTRODUCTION

Underwater wireless communication is a rapidly growing area of research and engineering. The interest in communicating underwater stems from several military and commercial applications which require transmission of data between two or more nodes located underwater. There has also been a growing interest in building distributed and scalable underwater wireless sensor networks (UWSN) that will provide performance enhancement for various underwater applications for pollution control, climate monitoring, deep sea exploration, gathering of scientific data, etc as described in [1].

Although radio and optical techniques can be used for very short range applications, acoustic signals are generally used for communicating underwater (UW). Radio waves that propagate underwater are the extra low frequency ones (30 Hz – 300 Hz), but these require very large antennas and extremely high transmission power .Optical techniques do not suffer from the problem of attenuation as much; however, they are affected by scattering. Moreover, optical communication requires very high precision in pointing a narrow laser beam in the right direction, which is still being perfected for practical use. Hence acoustic transmission looks like the best possible option for UW transmission for now. A comparison of the three transmission techniques in sea water is given in Table 1[1].

Again, there is demonstration of SISO (single input and single output) and MIMO (multi input and multi output) for underwater communications by using OFDM technique in Fixed-point implementation as well as floating point implementation as described in [2]. The data rates are 3.2 kb/s and 6.4 kb/s for SISO and MIMO systems, respectively.

In this paper, we investigate the implementation of OFDM modems for underwater high data rate transmission. Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission recently used for underwater communications. We first implemented OFDM in air and then in water and analyze the performance in both the cases. Thus it is very beneficial to use OFDM in underwater communications.

There are a few acoustic modems available, including commercial products such as [3]–[5], a model widely used in the research community [6], and experimental designs such as [7]–[10]. The designs in [3], [9], [10] are based on non-coherent frequency-shift-keying (FSK), and those in [4], [5], [8] are based on spread spectrum; all of them inherently have low data rate. The reconfigurable acoustic modem (rModem) of [7] has a flexible structure that can facilitate quick prototyping of different algorithms. The Micro- Modem of [6] has two operating modes: 1) a low-power low rate mode based on non-coherent FSK, and 2) a high-power high-rate mode based on coherent phase-shift-keying (PSK) [1].

The Micro-Modem shown in fig. [1] is a compact, low-power, underwater acoustic communications and navigation subsystem. It has the capability to perform low-rate frequency-hopping frequency-shift keying (FH-FSK), variable rate phase-coherent keying (PSK), variable rate phase coherent keying (PSK), and two different types of long base line navigation, narrow-band and broadband[6].

The rest of this paper is organized as follows. We describe the OFDM basics and transreceiver design in Section II. The results are presented in Section III for OFDM implementation in air and in Section IV for OFDM implementation in water. Section V concludes the paper.

Parameters	Acoustic	Radio	Optical
Speed of propagation	~1500 m/s	~33,333,33 m/s	~33,333,333 m/s
Power loss	>0.1 dB/m/Hz	~28dB/km /100MHz	Depends on turbidity of water
Bandwidth	~kHz	~MHz	~10-150MHz
Antenna Size	~0.1m	~0.5m	~0.1m
Frequency Band	~kHz	~MHz	$\sim 10^{14}$-10^{15}Hz
Effective Range	~km	~10m	~10-100m

Table1.Comparison of Acoustic, Radio wave, and Optical communication in seawater [1].

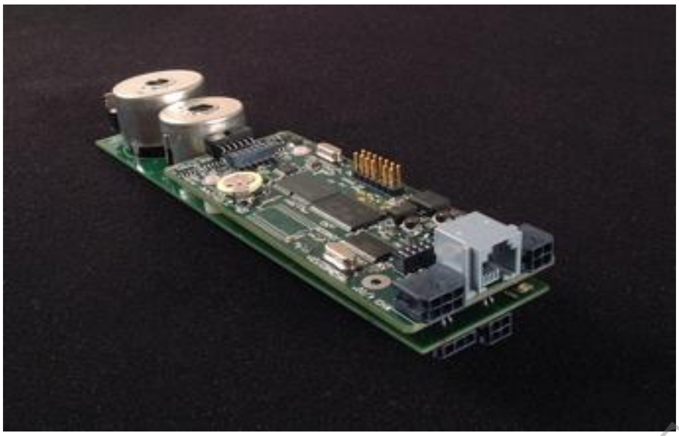

Fig.no.1. Basic Micro-modem board set: power amp and mainboard[6].

Section II
OFDM Basics

Orthogonality property: Orthogonal Frequency Division Multiplexing (OFDM) is a type of multicarrier modulation scheme in which the data bits are divided into several different bit streams in parallel, which are then transmitted using overlapping sub-carriers shown in fig.2 .It is possible to send out orthogonal signals (*i.e. sin(t) and cos(t)*) at the same frequency without interference between the two.This means we can allow the adjacent signals to overlap as long as they remain 90 degrees out of phase from each other. This will allow us to maximize our transmission rates.

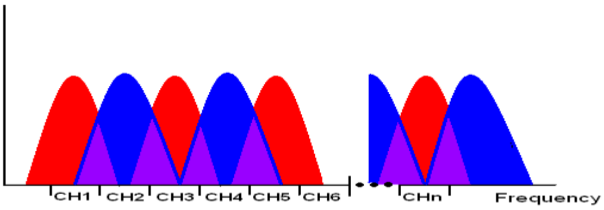

Fig.no.2.OFDM concept

Flat fading channel property: With many transmission schemes, the received signal is the transmitted signal convolved with the channel, y (n)=s(n)*h(n).This can potentially make recovering s(n) complicated. In OFDM, each value of s(n) is multiplied by only one value of h(n).This property makes h(n) known as a "flat fading" channel".

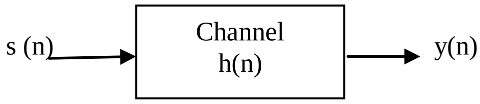

Fig.no.3. Flat fading channel property

Determining Signal Capacity: Increasing our transmission rate means increasing our transmission bandwidth. This also lowers our transmitted signal strength, decreasing the signal-to-noise ratio, SNR. Our signal capacity, C, is based on the bandwidth and the SNR

$$C = BW\log_2 (1+SNR) \qquad (1)$$

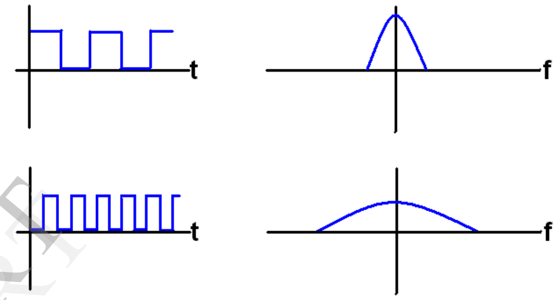

Fig.no.4. Determining Signal Capacity

Synchronization for OFDM:

Synchronization is a vital part of this process. Signal acquisition is achieved in two steps:
1) Estimation of symbol timing:
Signal recovery relies on training symbols which are composed of 2 identical halves in the time domain. Halves are made by transmitting arbitrary data at even frequencies and zeros at odd frequencies. Timing data is added as a prefix to actual data.
2) Detection of carrier frequency offset:
No two oscillators oscillate at the same rate. The oscillators in the receiver are slightly different than those in the transmitter. Decoding the original signal means accounting for the offset between the two oscillators.

Broadband applications has imposed great challenges for conventional single carrier transmissions, as the channel exhibits strong frequency selectivity that prevents effective channel equalization to remove inter-symbol-interference (ISI) at affordable complexity. Multi-carrier techniques divide the available bandwidth into a large number of overlapping sub bands, so that the symbol duration is long compared to the multipath spread of the channel.

Consequently, ISI may be neglected in each sub band, greatly simplifying the receiver complexity of channel equalization [11].

OFDM is an efficient multi-carrier implementation based on fast-Fourier-transform (FFT). Consider an OFDM transmission over a frequency selective channel, that is described by its discrete-time baseband impulse response vector $\mathbf{h} := [h(0), \ldots, h(L)]^T$, with L standing for the channel order. The channel impulse response includes the effects of transmit receive filters and physical multipath. By implementation an inverse FFT at the transmitter and an FFT at the receiver, OFDM converts an ISI channel into parallel ISI-free sub channels with gains equal to the channel's frequency response values on the FFT grid. Specifically, let K denote the number of subcarriers in the OFDM system, $x(p)$ as the transmitted symbol on the pth subcarrier, $y(p)$ as the received symbol on the pth subcarrier, the equivalent channel input-output relationship can be described by:

$$y(p) = H(p)x(p) + v(p), \quad p = 0, 1, \ldots, K-1, \qquad (1)$$

where $v(p)$ stands for the additive white Gaussian noise, and $H(p)$ is the channel's frequency response on the pth subcarrier:

$$H(p) = \sum_{l=0}^{L} h(l) e^{-j\frac{2\pi}{N_c}pl}, \quad p = 0, \ldots, N_c - 1. \qquad (2)$$

Channel equalization amounts to scalar inversion:

$$\hat{s}(p) = y(p)/H(p) \qquad (3)$$

on each subcarrier. The equalization complexity thus does not depend on the channel length. Precisely due to its low equalization complexity in the presence of highly-dispersive channels, OFDM has prevailed in recent broadband wireless systems. Those include digital audio/video broadcasting (DAB/DVB) standards in Europe, high-speed digital subscriber line (DSL) modems in the United States, digital cable television systems, and wireless local area networks [11].

A. Transreceiver Design

The transmitter diagram is shown in Fig.5. We use a graphics user interface to input some text messages. The transmitter first converts the text data into a binary format. The binary data is then interleaved and coded by a simple (3,1) repetition code for error correction. The coded data is mapped to QPSK (quadrature phase-shift keying) symbols. The symbol stream is partitioned into blocks, and each block is OFDM modulated. During the OFDM modulation, we insert pilot symbols at every 4th subcarrier, which facilitates channel estimation at the receiver for coherent demodulation. The modulation is implemented at baseband and then up-shifted to passband for transmission. A synchronization sequence is inserted in front of the data packets during transmission.

The receiver diagram is shown in Fig. 5. The receiver first applies bandpass filtering on the incoming data stream, then it looks for where the useful data begins via correlating the received data with the synchronization sequence template. Once the receiver has found a useful data packet, it downshifts the passband signal to baseband. We then estimate the carrier frequency offset (CFO) to correct any carrier mismatch between the transmitter and the receiver. After CFO compensation, we rely on pilot tones to estimate the channel frequency response. With coherent demodulation at each OFDM subcarrier, we decode the (3,1) repetition coding using maximum ratio combining. The receiver finally extracts the binary bits from the QPSK symbols and generates the text message [11].

B. Graphic User Interface

There are two graphical user interfaces (GUIs), one for the transmitter and one for the receiver. These interfaces allow for configuration of basic parameters such as

- Number of OFDM subcarriers
- First carrier frequency
- Guard time between data packets
- Synchronization sequence duration
- Center frequency for synchronization sequence
- Bandwidth of synchronization sequence
- Pause time between synchronization sequence and first data packet
- Number of packets per transmission
- Repetition coding rate
- Number of edge channels deactivated

The receiver has a few extra parameters including the Correlation threshold, the amplitude trigger and the channel length. The receiver also gives the user the option of checking the bit error rate and plotting each channel estimation graph during the CFO estimation process[11].

C. Packet Formation

The typed text messages have different lengths, while the packet has a fixed length. Hence, different number of packets may be required for different messages. To create an automatic message transmission, we design the packet format as follows. The binary sequence created by the transmitter consists of the text data along with 2 metadata bits (administrative bits) at the end. These metadata bits are known as the partial packet bit and the continuation bit, respectively. The continuation bit will tell the receiver whether the next transmission contains a continuation of the current transmission. The partial packet bit alerts the receiver that the text data was not able to fill the packet and extra meaningless data have been inserted, which must be removed at the receiver end. In this case, eleven extra bits must be added before the partial packet bit to identify the length of the useful data (and where the meaningless data begins). The format of the binary data in a packet can be seen in Figs. 6. On the transmitter end, the maximum allowable data length

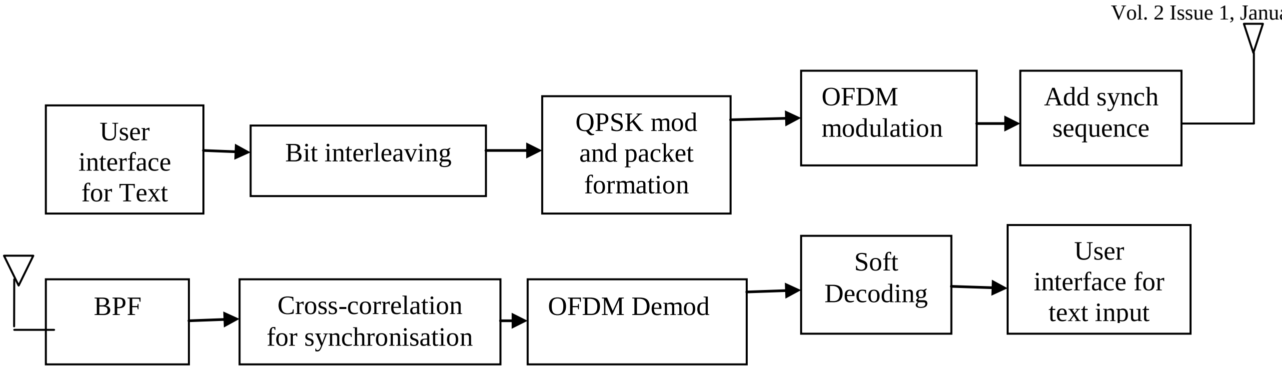

Fig.no.5.Block diagram of Transmitter (Top) and Receiver (Bottom) [11]

determines what the metadata bits are set to. If the length of the binary data is equal to the maximum allowable data length minus two, the transmitter will set both of the metadata bits to zero. If the binary data length is greater than the maximum allowable data length minus 2, the transmitter will break the data up into multiple transmissions, set the partial packet bit to zero, and the continuation bit to one. If the data length is less than the maximum data length minus thirteen, meaningless data is added to the end of the sequence. The eleven identifying bits are added to the end of the meaningless data and the partial packet bit is set to one while the continuation bit is set to zero. If the data length is between the maximum allowable data length minus two and the maximum allowable data length minus thirteen, the binary sequence is zero padded (to make the data length equal to the maximum allowable data length, zeros are added between the end of the useful data and the meta data) and both the partial packet and continuation bits are set to zero. These zeros will not be removed by the receiver but will not affect the received data. The point to placing meaningless data in the partial packets (as opposed to just zeros) is to ensure that the peak-to-average ratio of the OFDM symbol is randomized [11].

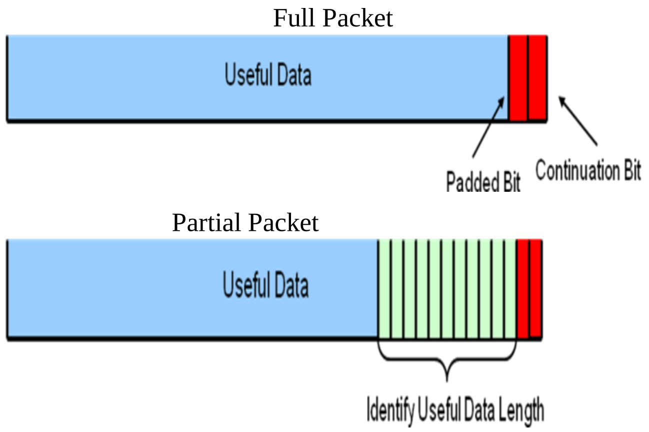

Fig.no.6.Packet formation [11]

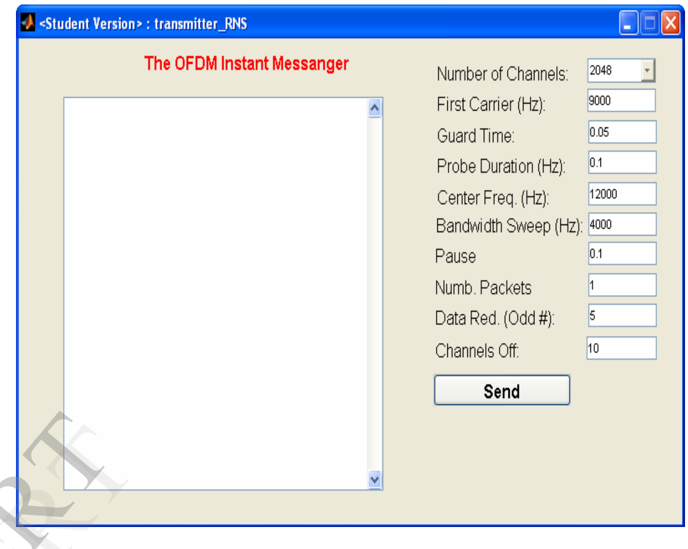

Fig.no.7.Transmitter GUI [11]

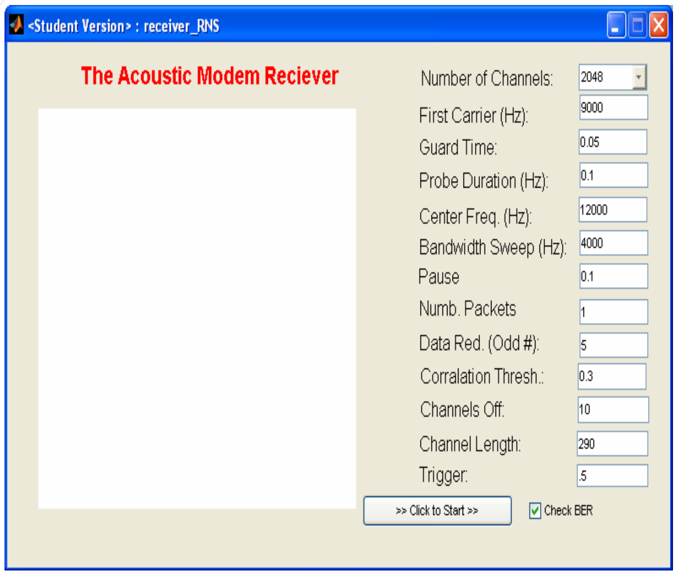

Fig.no.8.Receiver GUI [11]

Section III

In this paper, we investigate the implementation of OFDM modems for underwater high data rate transmission. We first implemented OFDM in air and then in water and analyze the performance in both the cases. Thus it is very beneficial to use OFDM in underwater communications.

Our demonstration has two settings. In the first setting, we demonstrated multicarrier OFDM transmission and reception in air. The testbed is depicted in Fig.9, where a speaker together with a laptop serve as the transmitter, and a together with another laptop serve as the receiver. A typical micro-phone channel impulse response is shown in Fig. 10, where we clearly see the dominant line-of-sight path. In the second setting, we demonstrated OFDM transmission and reception in water. The testbed is depicted in Fig.11. The underwater speaker and hydrophone are used as transmitting and receiving devices, respectively. A typical channel impulse response is shown in Fig. 12, where we clearly see the reverberation effects. The last path is about 37 meters longer than the first path inside the water tank of 2 meters long, 0.5 meters wide and 0.5 meter deep. Hence, the transmitted signal has bounced back and forth between the hard surfaces of the water tank a plenty of times. We can also see the amplitude attenuation associated with each bounce [11].

TRANSMISSION IN AIR

The OFDM burst, which was generated in the 3-5 kHz band using MATLAB, was transmitted via soundcard using a speaker connected to the computer. The acoustic transmission impinged on microphone connected to the sound card in a second computer. This second computer acted as the OFDM receiver (implemented in MATLAB) and estimated the received bits. Hence the channel in effect consisted of a combination of two sound cards, speaker, air, and microphone. Several issues such as timing synchronization, carrier frequency offset estimation and correction, and channel equalization had to be taken into account for the system to be operational at usable bit error rates. Since the experiment was conducted in an indoor environment which contained tables, chairs, computers, and shelves, the received signal was subject to multipath. Recall that sound travels about five times slower over air when compared to underwater. This results in a larger propagation delay as well as a more pronounced Doppler effect at much slower speeds. Hence the over-the-air channel is in some ways less conducive for acoustic transmission when compared to its underwater counterpart [1].

CFO ESTIMATION

We will use the block-by-block receiver structure of [2]. The channel time variation within each OFDM symbol is modeled as a multiplicative process $ej2\pi\epsilon t$ on the received signal after the multipath propagation, where ϵ is termed as carrier frequency offset (CFO).We use null subcarriers to facilitate the finding of the CFO.The idea is as follows. We collect the baseband samples for each OFDM block. For each tentative €, we compensate the CFO on the OFDM block and evaluate the FFT output on the null subcarriers. The energy of the null subcarriers is used as the cost function $J(\epsilon)$. If the receiver compensates the data samples with the correct CFO, the null subcarriers will not see the intercarrier interference (ICI) from neighboring data subcarriers [12].

$$€ = \arg\min J(€) \quad (4)$$

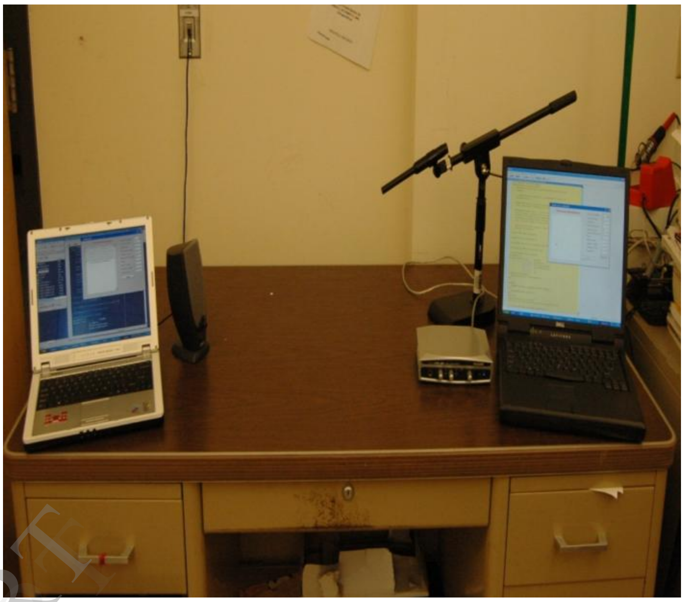

Fig.no.9. Transmission in air [11]

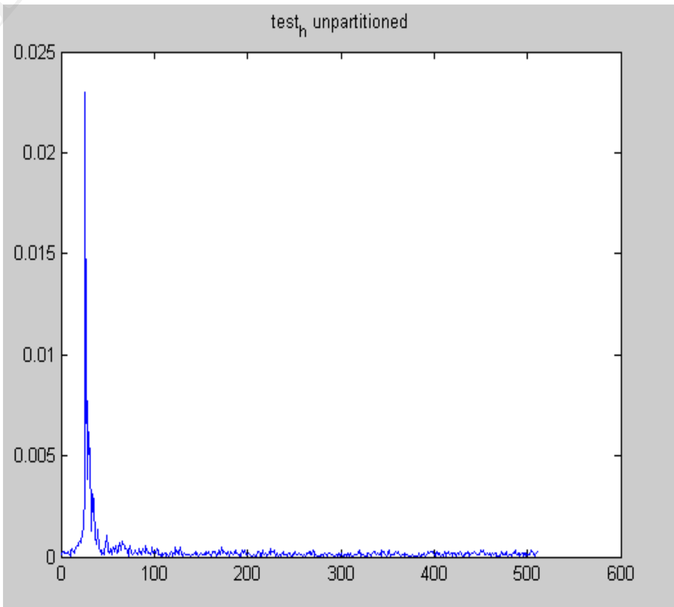

Fig.no.10.Estimated Channel Impulse Response for In-Air Transmission (2048 Subcarriers) [11]

TRANSMISSION IN WATER

We demonstrated OFDM transmission and reception in water. The testbed is depicted in Fig.11.The underwater speaker and hydrophones are used as transmitting and receiving devices, respectively. A typical channel impulse response is shown in Fig. 12, where we clearly see the reverberation effects.

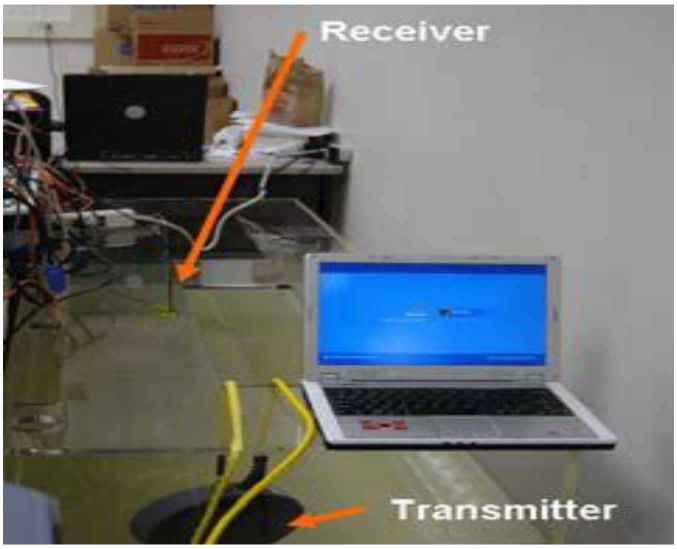

Fig.no.11 Transmission in Water [11]

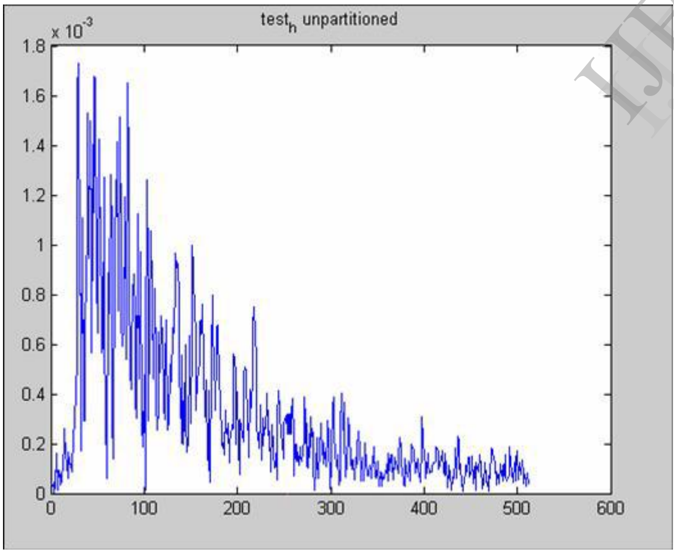

Fig.no.12Estimated Channel Impulse Response for Underwater Transmission (2048 Subcarriers) [11]

Sr.No.	Parameters	Air	Water
1.	CFO Estimation	No CFO estimation	CFO is estimated
2.	Delay Spread	5.3ms	31.1ms
3.	No. of subcarriers tried(K)	256,512,1048,2048	2048
4.	Sampling Rate mismatch	Ignored(no. of subcarriers large) considered (no. of subcarriers large)	Considered (as large delay spread)

Table.no.2. Comparison of OFDM parameters in Air and in Water

The table shows the basic difference in OFDM implementation techniques in air and in water.

Section IV
CONCLUSION

In this paper, we investigate the implementation of OFDM modems for underwater high data rate transmission. There are many advantages of OFDM Acoustics modems in underwater communications. The OFDM basics give us the broad idea about OFDM techniques. We have first demonstrated OFDM in air and then in water. The channel impulse response shows a big difference in delay spread.The system will be able to transmit text.Clear line of sight between transmit receiver is observed.Integration into a fully functional Modem can be possible.

Transmission of other forms of data (voice, image etc.can be send. Integration into other network like Wi-Fi can be made possible. The implementation effort in this paper provides some useful insights towards realizing a practical OFDM modem for high-data-rate and reliable underwater acoustic communications.

REFERENCES

[1] Arjun Thottappilly"OFDM for Underwater Acoustic Communication" thesis submitted on August 17th, 2011 Blacksburg, Virginia.

[2] Hai Yan, Shengli Zhou, Zhijie Shi, Jun-Hong Cui, Lei Wan, Jie Huang, and Hao Zhou" DSP Implementation of SISO and MIMO OFDM Acoustic Modems" The Underwater Sensor Network Lab, University of Connecticut, Storrs, CT 06269, USA.

[3] Benthos, Inc., "Fast and reliable access to undersea data," http://www.benthos.com.

[4] Link Quest, Inc., "Underwater acoustic modems," http://www.linkquest.com/html/uwm hr.pdf.

[5] DSPCOMM, "Underwater wireless modem," http://www.dspcomm.com.

[6] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI Micro-Modem: An acoustic communications and navigation system for multiple platforms," in *Proceeding of OCEANS*, 2005.
[7] E. Sozer and M. Stojanovic, "Reconfigurable acoustic modem for underwater sensor networks," in *Proc. First ACM International Workshop on Underwater Networks*, Los Angeles, CA, Sept. 2006.
[8] T. Fu, D. Doonan, C. Utley, R. Iltis, R. Kastner, and H. Lee, "Design and development of a software-defined underwater acoustic modem for sensor networks for environmental and ecological research," in *Proc. of OCEANS*, Sept. 2006.
[9] J. Wills, W. Ye, and J. Heidemann, "Low-power acoustic modem for dense underwater sensor networks," in *Proc. of WUWNet*, Los Angeles, CA, Sept. 2006.
[10] B. Benson, G. Chang, D. Manov, B. Graham, and R. Kastner, "Design of a low-cost acoustic modem for moored oceanographic applications," in *Proc. of WUWNet*, Los Angeles, CA, Sept. 2006.
[11] Sean Mason, Robert Anstett, Nicoletti Anicette, and Shengli Zhou" A Broadband Underwater Acoustic Modem Implementation Using Coherent OFDM" on The National Conference of UnderGraduate Research (NCUR), Domician University of California, April 12—14, 2007.
[12] H. Yan, S. Zhou, Z. Shi, and B. Li, "A DSP implementation of OFDM acoustic modem," in *Proc. of the ACM International Workshop on UnderWater Networks (WUWNet)*, September 14, 2007.