High Rate OFDM Acoustic Link for Underwater Communication

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ABSTRACT

A high bit rate acoustic link over an underwater channel is investigated . Design of a Digital communication system utilizing acoustic signals for underwater applications is a very challenging field due to the extremely complex nature of the underwater channel. The conventional techniques for overcoming the channel effects used in communication systems elsewhere fail to give the desired results when applied in this field of communications. This paper aims at designing one such system, which can effectively withstand the adverse effects of the channel but still provide adequate data rate. For this purpose, an in-depth study of the underwater communication channel was carried out and the findings are analyzed. Orthogonal Frequency Division Multiplexing has been selected as the modulation scheme, deviating from the more conventional single-frequency methods hitherto used in this field in the past. A relatively simple but robust communication system has been designed covering techniques ranging from Communications, Acoustics and Signal Processing. The inherent features of the OFDM scheme make the system rugged against channel effects such as extremely strong multi-path and additive noise. Additional features have been incorporated to make the system immune to Doppler shifts and hardware instabilities. The system has been put through simulated as well as real channel conditions and the results have been presented.

Keywords: Orthogonal Frequency division Multiplexing ;Acoustic; Underwater Communication ;Multipath; Digital Signal Processing;Doppler Shifts;Channel Conditions

I. INTRODUCTION

In the past five to ten years, there has been a tremendous increase in research and development of underwater acoustic (UWA) communication systems. The growing interest in UWA communications came as a response to the rapidly growing needs for wireless underwater communications, brought in part by the broadening of applications, which were almost exclusively military, to commercial ones. Commercial applications, which have received much attention lately, are pollution monitoring in environmental systems, remote control in offshore oil industry, and collection of scientific data recorded at benthic stations without the need for retrieving the instruments. Many of the applications, both commercial and military, are now calling for real-time communication with submarines and autonomous underwater vehicles.

The major constraint in using this underwater medium is the extremely complex and continuously varying nature of the sea. Nevertheless, this underwater channel has been used (sparingly) and the most common mode of underwater communication is acoustic waves. The modest usage of the underwater medium, hitherto, has been restricted to analog voice communication systems, with some capability for data communication using Frequency Shift Keying or Amplitude Shift Keying. These initial digital communication systems offered a very low rate of communication (less than 300 bits per second) and were most often unreliable. Hence they were confined to only emergency usage and have not been exploited in the true sense of tactical communications. But now, there is a strong requirement for exploring and exploiting a method for High-Speed Digital Underwater Communications. Added to the speed of the communication, the other issues of equal importance are the **reliability** and **robustness** of such a Communication System to withstand the complex and continuously changing nature of the underwater medium. For the Defense applications, secrecy and security of the information from detection and interception are added constraints for the designer of such a communication system.

Aim of the Paper: With the requirements as discussed above, the aim of the paper is to design a Digital Acoustic Underwater Communication System with the specific requirements as stated below:

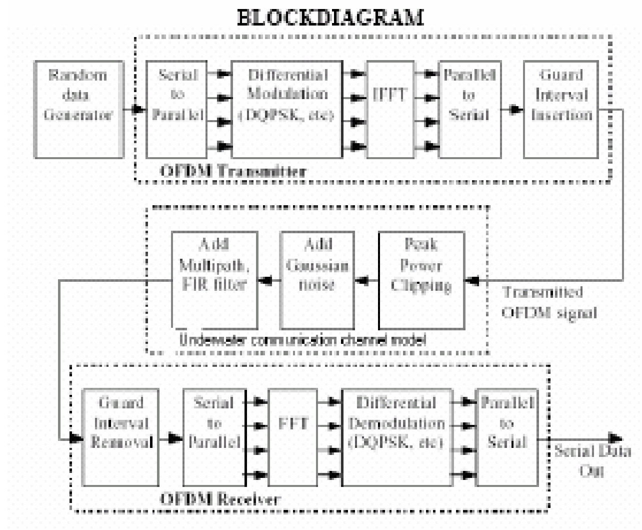
a) The system should be robust as regards the underwater channel and should be able to effectively counter the effects of strong multi-path and time varying nature.

b) The system should have an effective bit rate comparable to and in excess of similar systems currently in use

c) The range of operation to be at least 1 km and with depths of minimum 300m.

1.2 The total work of research and implementation was divided in the following phases:

PhaseI – The Design: The design of the under water communication channel is to be translated into code using MATLAB for preliminary testing and modifications. The completed code is to be tested on simulated underwater channel model for confirmation regarding the specifications being met. A real life simulation to be carried out by making use of an acoustic tank and available lab hardware. This will ensure that the model is in step with the hardware implementation difficulties, and suitably incorporate them into the design. The basic block diagram of the complete system is as shown below.



Phase II : **The implementation:** In this phase, the MATLAB design, which has been tested and proved in phase II, should be implemented. This aim here is to create a stand-alone system meeting all the requirements.

1.3 Theory : The OFDM signal can be represented by the following equations

Complete Signal Representation

$$s(t) = \sum_{k=1}^{N} b_k e^{j2\pi f_k t} e^{j2\pi f_c t} p(t - N\tau)$$

b_k = k^{th} bit

f_k = k^{th} sub-carrier

f_c = Carrier Frequency

N = number of sub-carriers

$p(t-N\tau)$ = pulse shaping function

Base-band Signal Representation

$$s(t) = \sum_{k=1}^{N} b_k e^{j2\pi f_k t}$$

$$f_k = k^{th} sub - carrier = \frac{k}{N}$$

$$s(t) = \sum_{k=1}^{N} b_k e^{j2\pi \frac{k}{N} t} = IFFT(b_k)$$

The base-band signal representation clearly shows that the OFDM signal is no other than an Inverse Fourier transform operation. A basic block diagram of an OFDM transmitter is shows in figure .

Figure : Basic block Diagram of OFDM transmitter

An OFDM signal can then be demodulated using Fourier Transform. Fourier Transform is just the inverse of the Inverse Fourier Transform which is capable of perfectly demodulation the signal assuming noise free and interference free signal [1][2][3][9]. The receive signal is first serial to parallel converted to allow block demodulation using the Fourier Transform. The signal is then pass through a detector to decode the signal back into its original data. Figure 1.3 shows a design of an OFDM receiver using the Fourier Transform

.

Figure : OFDM receiver with Fast Fourier Transform (FFT) Operation

The receive OFDM signal can be represented by the following equation:

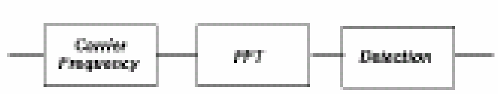
Base-Band representation

$$b_k = \frac{1}{N}\sum_{k=1}^{N} r(t)e^{-j2\pi f_k t}$$
$$= FFT[r(t)]$$

r(t) = received signal
b_k = k_{th} *bit*
f_k = k_{th} *sub-carrier*
N = number of sub-carriers

The base-band signal representation clearly shows that the data can be demodulated by using the
Fourier Transform.

Figure is the basic block diagram of an OFDM receiver.



Section 3: Bit Error Rate Simulation

For the simulation, a frequency selective channel is model as follow:

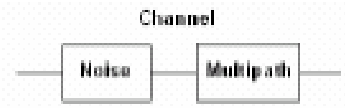


Figure 15: Channel Model

$$r(t) = \sum_{l=0}^{L} h(l)s(t-l) + AWGN$$

s(t) = transmitted signal
r(t) = received signal
L = number of multipath delay path

LAYOUT OF THE REPORT

Design of a communication system requires a complete understanding of the channel in which the system to operate and its effects. Knowledge of the currently existing systems is also necessary in the design process. This report, in addition to the current introductory chapter, is organized into various parts. First part discusses the underwater channel and the various Underwater Communication Systems reported in theliterature. As will be seen, the literature survey has resulted in the selection of a modulation scheme OFDM for use in the project. Hence second part gives a brief introduction to OFDM and its suitability for usage in underwater communication.Then we deal with the transmitter design and receiver design respectively.After the design the next part includes the simulation, observations and inferences. . The concluding chapter gives the reference's used for the paper .

2 THE UNDERWATER ACOUSTIC CHANNEL

The underwater acoustic communication channel is extremely complex in nature. The complexity arises from the fact that the channel is not perfectly homogeneous. The numerous imperfections are mainly due to density and temperature gradients and the non-homogeneities of the water due to suspended particles of solid or gaseous matter. The constant water motion and the channel boundaries like the bottom and the surface further increase the complexity. The effect of such complex nature of the channel is the strong multi-path phenomenon and the Doppler spread. These phenomena are themselves not constant and are continuously varying. When viewed from a communication system designer's point of view, the four aspects that are of fundamental concern are namely:

a) Multi-path phenomenon causing Inter-Symbol Interference and reverberation.
b) Transmission Loss due to geometrical spreading and absorption
c) Ambient Noise
d) Doppler Spreading due to relative motion between the transmitter and receiver.
It is to be noted that all the four aspects listed above are continuously varying in nature and the communication system design needs to constantly track these variations to effectively mitigate their effects.

The following paragraphs further elaborate the above stated aspects.
a) **Multi-path Phenomenon**: This is the most challenging aspect of the underwater acoustic channel. The boundaries of the surface and bottom reflect the energy; so numerous travel paths exist between the transmitter and the receiver. This is further complicated by imperfect boundaries. The whole phenomenon results in time dispersal of the signal. This time spreading can be as high as hundreds of milliseconds inshallow water to several seconds in deep waters. At high frequency, the total time spread is less due to absorption at boundaries and attenuation in water.
b) **Transmission Loss**: The acoustic wave reduces in intensity as it propagates through the medium due togeometrical spreading and absorption mechanism. Though the attenuation of acoustic waves in water isnegligible as compared to the RF waves in water, there is considerable loss in energy due to absorptionmechanism in water. The loss due to geometrical spreading can be either spherical or cylindrical in nature.
The loss per unit range is a strong function of frequency and is given
by $TL(f) = 20LogR + \alpha(f).R$ where TL is the transmission loss in dB, '*f*' is the frequency and 'α' is the absorption function .
c) **Ambient Noise**: Ambient Noise influences the received Signal to Noise ratio and largely controls the transmitter power. It generally decreases in frequency over the range of interest. Inshore environment and marine worksites are more noisier than deep ocean environment and the communication system design eeds to cater for the worst case performance conditions. The platform noise from which the system operates also needs to be considered despite the efforts to isolate the transducers. Knudsen curves give a good insight into the ambient noise in the underwater medium.
d) **Doppler Spread**: This is introduced by relative motion between the transmitter and receiver, or by otion of the water. The shift is 0.35 Hz / (knots. KHz) one way , or 0.70 Hz / (knots. KHz) two way of relative motion. Due to the scarcity of channel bandwidth (caused by absorption losses and projector transducer characteristics), Doppler spread may easily result in further reduction in available bandwidth. This is because some allowances for guard band must be made especially for FSK systems.
2.1 Due to harsh underwater acoustic medium described above, many well known communication techniques cannot be applied and hence the design is a compromise between data rate, reliability and distance. The combined effects of the above mentioned phenomenon have led in the past to system design based exclusively on noncoherent detection and low signaling rates. Approaches to system design depend upon the technique used for overcoming the effects of multi-path and time variations. These can be classified into broadly into 1) the signal design, i.e., the choice of modulation / detection method and 2) the transmitter / receiver structure, i.e., the choice of equalization method.
2.2 The nature of the channel dictates the equirement of long symbol durations to avoid Inter Symbol Interference (ISI) and better integration, whereas the symbol duration needs to be as small as possible for high data rates. Small symbol durations mean the ISI is spread across a large number of symbols. This explains the requirements of a robust equalization technique at the receiver. Further the time varying nature of the channel requires an adaptive equalizer operating in the decision directed mode to keep track of the channel. Initially, this has led to the design of systems, which has been highly complex in nature but not delivering in terms of the data rate. Focused efforts over the years in this field have resulted in underwater communication using acoustic waves progressively improving both in terms of data rate and distance. Table 3.1 shows a summary of performance metrics for some Underwater Acoustic Modems

Table3.1. A Summary of performance merits for some UWA modems presented in the literature. S indicates a shallow water result, while D indicates as deep water result, generally a vertical channel. In order to design a system which can give high data rates but at the same time overcome all the channel effects such as strong multi-path, extremely high ISI, Doppler spread etc, we need a modulation scheme that is inherently robust against multi-path and yet give high data rates. One such scheme is Orthogonal Frequency Division Multiplexing (OFDM) or Multi-carrier modulation. OFDM inherently breaks the high data rate bit

stream into parallel low speed bit streams, which are individually modulated on to carriers, orthogonal to each other. These results in longer symbol durations and thus better integration intervals.

3. OFDM PARAMETERS SELECTION

3.1 The main parameters which need to be fixed in the transmitter are namely,

- Sampling Frequency, Fs
- Number of FFT and IFFT points, N
- The length of the cyclic prefix, as a fraction of the symbol duration
- The modulation scheme of the individual sub-carriers.

The selection of Fs and N automatically fixes a number of other dependent parameters such as

i) The symbol duration (T) without the cyclic prefix. This is because,

T = N / Fs

ii) The number of frequency bins (N) and the bin spacing or the carrier separation, (Fs / N)

iii) The number of bins falling within the bandwidth of interest i.e., from 6 KHz to 9 KHz, and hence the number of sub-carriers available for modulation. The indices these useful bins into the N-point IFFT can also be ascertained.

3.2 The selection of the cyclic prefix length and the modulation scheme of individual carriers affect the data rate and the robustness of the system to channel effects. In this project, the limitations in the selection of the parameters are:

- .
- The minimum sampling frequency needs to be about 2.56 times (or at-least 2 times) the value of maximum frequency content (i.e., 9 KHZ) of the signal.
- The length N, of the FFT or IFFT needs to be a power of 2, for ease of processing.
- The symbol duration needs to be more than 30 msec in order to overcome the effects of multi-path and hence the ISI. This will also ensure a better integration at the receiver end when the symbol is being detected.
- The sub-carrier spacing needs to be more than the maximum deviation due to Doppler shift. If this limitation is to be overcome, there has to be a suitable algorithm for Doppler compensation.

Higher sub-carrier spacing results in lesser Inter-Carrier-Interference (ICI) due to minor drifts in sampling rate, but the downside is the reduction in data rate.

3.3 It can be seen that the selection of the above-mentioned parameters is an iterative one, and any set of parameters is a trade off between integration time of the symbol duration, immunity to ISI and Gaussian Noise; and the data rate. The communication system being reported has the following set of parameters :-

Table 3.3 :

Sampling frequency	**32768 Hz**
FFT and IFFT length	**1024**
Guard time / Cyclic prefix	**3.906 ms**
Subcarrier modulation	**DQPSK**
Symbol duration without cyclic prefix	**31.25 ms**
Symbol duration with cyclic prefix	**35.1562 ms**
Number of carriers used	**96**
Carrier spacing	**32 Hz**
Frequency band of usage	**6016 Hz to 9088 Hz**

3.4 To increase the transmission rate we generate twelve such basebands in the frequency range 6016 Hz to 9088 Hz .Each such baseband accommodates 5460 bits. Thease subbands are then frequency shifted so that they occupy frequency range 28672 Hz to 65536 Hz .Frequency shifting is done by modulation and filtering techniques. This gives effective bit rate of 65520 bits per second.

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1 The trials and tests of the Communication System discussed in the previous chapters can be broadly categorized into two types, namely, 1) Simulation of the channel within the same computer and 2) Trials carried out in the acoustic test water tank. These are considered separately in the following paragraphs.

Trials on Simulated Channel

4.2 Channel Model: An underwater acoustic communication channel, as discussed in Chapter 3, has the four main characteristics

- Multi-path phenomenon

- Transmission Loss
- Additive Noise
- Doppler Effects

Any channel model of the underwater medium needs to incorporate the above four features. The hypothetical channel considered for the purpose of simulation has the following characteristics:

- Channel length 2000 m
- Depth of channel 300 m
- Transducers depth 50 m
- Loss due to bottom / surface bounce 3 dB

Under the above conditions, there can be multiple paths between the transmitter and the receiver. Not all of the secondary paths have sufficient strength to interfere at the receiver. For the purpose of simulation, we an consider a direct path and a few indirect paths. The signal arriving from the indirect paths are reduced in strength due to the extra distance traversed (hence more path loss – proportional to the extra distance) and one or more bottom / surface bounce loss. It can be safely concluded that the strongest of the indirect path signals are at least 4 dB below the direct path signal. This means that its strength is 0.63 times the strength of the direct path signal. The next issue is the extent of delay of the indirect path signal. Since it traversed the extra distance, the delay is the time taken for the sound wave to travel this extra distance in the water medium. The underwater channel considered above can be modeled as a FIR filter with the tap delays equal to the delay of each indirect path signal arriving at the receiver and the coefficients are the relative strength of these signals with respect to the direct path signal. For the first set of Simulations, one indirect path signal of strength 0.63 and delay of 56 milliseconds is considered. The Additive noise is added in the channel such that the SNR varies from 0 dB to 30 dB. This model of the channel simulates strong multi-path effects, propagation loss, and additive noise. The transmitter itself simulates the Doppler effects by sending out a re-sampled waveform. Simulations were carried out over the channel discussed above by considering a random set of 50,000 bits for each simulation. The simulation results are as follows :

No multipath effect for SNR = 8 dB   BER = 3 in 1000 ;

SNR= 10 dB   BER = 3 in 10000;

With Multipath effect   for SNR = 8 dB BER = 2 in 100

SNR = 10 dB BER = 1 in 100.

4.3 TRIALS IN ACOUSTIC TEST TANK

The trials carried out using actual hardware and transducers required a suitable acoustic test tank. The worst-case scenario would be a shallow water tank where there would be strong multi-path reflections from the tank walls, which interfere with the main direct path signal. The delay here between various signals following different paths would be of the order of only a few milliseconds. Because of relatively close proximity of the tank walls, the indirect path signals would be comparable in strength to the main path. For this purpose, a static Fire Main Tank was identified, which was a circular tank of diameter about 5 m and depth 1.5 meters. This would be a very good Trials tank for the reasons discussed above. The transducers were placed at about 0.5 m depth. The positions of the transducers were changed from diametricallyopposite to various other combinations. The trials conducted were of limited in nature for the SNR .

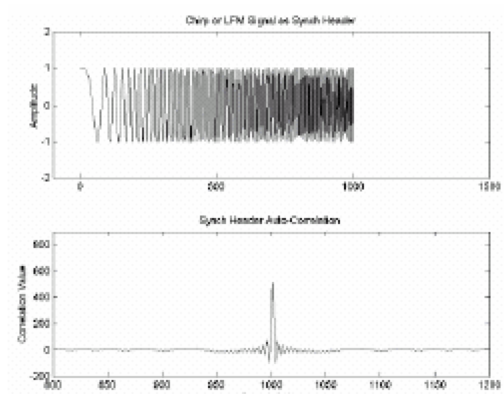


Figure1

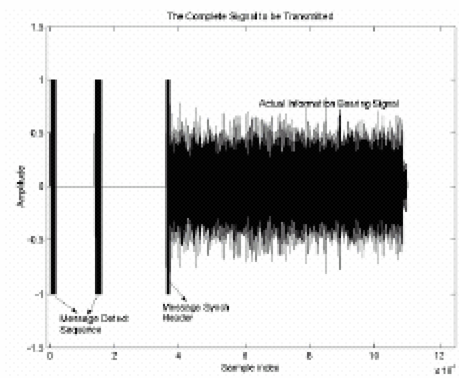
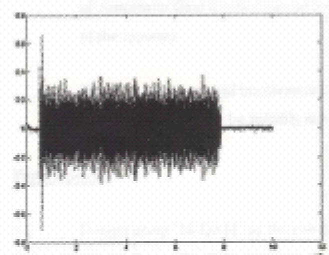


Figure 2



The recieved signal

Figure 3

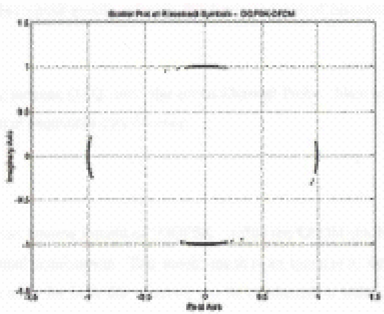


Figure 4

The message sync header signal is shown in figure 1. Total end-to-end (i.e., from the originating text file to the demodulated text file) trials were conducted . The results obtained were extremely encouraging. The transmitted signal is as shown in the figure 2. The received signal in one such trial is shown in Figure 3. The initial channel probe / message detect algorithm worked exactly as expected. No difficulty was ever faced by the receiver in these trials in synchronization. The transmitted and the received message texts compared exactly. The scatter plot is shown in Figure 4. The SNR was also calculated for each case. Theprocedure followed was to find the power of the noise alone (where the signal was absent, i.e., before or after the signal transmission) and the power of the 'signal + noise'. Calculations using these two quantities gave the SNR. The burst data rate was calculated for each trial and the rates achieved were consistently in excess of 5460 bits per second.

5 CONCLUSION AND FUTURE SCOPE

5.1 An acoustic data communication system has been designed for 'Underwater Channel' with the features as brought out in first part. A modulation scheme namely, OFDM has been used in the design of the system, deviating from the conventional path of using 'Single Carrier-Frequency Systems' for such applications. The simulation yielded results comparable with the conventional systems. The performance of the system in actual trials in Acoustic Test Water-Tank further proves the efficacy of such a modulation scheme. The system could prove the concept of high data rate using OFDM for underwater applications.

In the case of implementation on a special purpose DAQ card, the initial Channel Probe / Message Detect algorithm may be suitably modified, and Barker sequences may be used.

FUTURE SCOPE

5.2 Design using '16-QAM' as the sub-carrier modulation scheme instead of 'DQPSK' within the OFDM can be done. It will use Single-Tap Pilot-tone based Adaptive Sub-band equalization. This would result in an increase in data rates in excess of 256kbps. Once completed, the trials for both the versions can be conducted in realistic environment (the lake, for example). This would give a better insight into the performance of the system, its drawbacks, and its operation in the presence of Doppler due to constant movement of the platforms (rolling and pitching) even in the absence of relative motion. Based upon the results of these trials, a suitable Forward Error Correction scheme can be evolved to cater for the errors occurring in the channel. This will obviously result in the reduction in the available bit rate but will greatly enhance the reliability and robustness of the system to the channel.

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Table 3

S.No.	Type	Year	Data Rate(b/s)	Bandwidth (KHz)	Range (Km)
a)	Noncoherent	1984	1200	5	3.0 S
b)	Noncoherent	1991	1250	10	2.0 D
c)	Noncoherent	1997	2400-600	5	10.0 D - 5.0 S
d)	Coherent	1989	500,000	125	0.06 D
e)	Coherent	1993	600-300	0.3 - 1	89S - 203 D
f)	Coherent	1994	20	20	0.9 S
g)	Coherent	1998	1670-6700	2-10	4.0S - 2.0 S