Underwater Acoustic Communications:

Design Considerations At the Physical Layer Based on Field Trials

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***Abstract*— An overview of the unique challenges in underwater acoustic (UWA) communication in ocean environment is presented. The UWA channel is compared with conventional RF channels. Several design considerations applicable to the physical layer design of a UWA communication system is described based on field measurements. The unique problems in synchronization under high Doppler are described highlighting the key differences in the way Doppler affects the RF and UWA channels. A novel timing synchronization mechanism has been introduced in this study which caters for both the sampling skew offset and the Doppler shift between the transmitter and the receiver.**

Keywords- UWA; Doppler; OFDM; Synchronization; LFM;

I. Introduction

The field of wireless communications has made rapid strides in the past two decades due to the availability of improved DSP algorithms and high performance hardware platforms for their implementation. On comparing the performance improvement and services that are available in RF systems, it is seen that acoustic wireless systems lag behind by several orders of magnitude. Extensive channel measurements and field trials were conducted using a flexible test-bed towards identifying the key technical challenges and implementation issues for an underwater wireless acoustic modem capable of delivering moderately high data rates [1, 2]. This paper highlights the conclusions drawn from this study and pointing out to promising future directions.

The paper is organized as follows. In Section II, an overview of underwater acoustic channels and their properties is presented. A comparison is made between RF and shallow underwater acoustic channels to outline the differences in the various parameters. The various channel parameter measurements conducted are explained Section III. Section IV is devoted to design considerations for an acoustic modem. Synchronization issues unique to UWA systems are discussed in Section V and an innovative method for time synchronization and Doppler compensation is presented. We conclude the paper in section VI along with a discussion on future work.

II. Underwater Acoustic Channels: Challenges

In this section, we discuss the effects of the ocean environment on the performance of UWA communication systems. The traditional RF wireless communication systems use electromagnetic waves which are ruled out in favor of acoustic signals in the case of underwater wireless systems due to the large attenuation offered by the medium for electromagnetic waves [3]. Moreover, it is seen that the attenuation of the medium increases linearly with frequency in the case of acoustic signals. The range performance of an underwater communication system has primarily to do with the choice of the carrier frequency and band width which are used for the data transmission. The main parameters which decide the performance of an underwater wireless system are 1) the transmission loss, 2) ambient noise and 3) sound velocity profile which varies both temporally and spatially. A good physical insight into the channel properties is necessary to decide on the various strategies and techniques for mitigating the detrimental effects during data transmission. The table-I [4] compares the underwater acoustical channel to terrestrial RF channels. It is important to note the large multipath time dispersion and hence low coherence bandwidth. The underwater channel is typically a double spread channel in that it has both time dispersion and frequency dispersion. Due to high delay spread, spectral nulls will be present in the channel transfer function. The channel will exhibit both frequency selective fading and fast fading. The total available bandwidth will be constrained by the transducers used as well as the range. The underwater channel has the combination of the worst properties of both terrestrial cellular channel (high multipath and fading) and satellite channel (low SNR).

TABLE I

COMPARISON OF UNDERWATER CHANNELS AND RF CHANNELS

Channel	Coherence Bandwidth	Delay Spread	Doppler Spread
Troposcatter	1MHz	1µs	0.1 -10 Hz
Ionosphere	100Hz-10kHz	100µs – 10ms	0.1Hz – 100Hz
Outdoor	1MHz	1µs	10Hz
Indoor	1-10 MHz	0.1 – 0.5 µs	-
Underwater Acoustics	*0.3-Several Hz*	*0.3ms – 3s*	*3 – 60Hz*

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There is significant difference between the behaviour of horizontal and vertical (e.g. sea bed to sea surface or vice versa) transmission channels [5]. The horizontal channel is characterized by very high delay spreads and frequency selective fading. The vertical path on the other hand is much more constrained with respect to delay spread and the data rates achievable in vertical channel can be an order of magnitude greater than those for the horizontal channels.

III. CHANNEL MEASUREMENTS

The measured impulse response in a mini acoustic tank (at NPOL Cochin) with tx-rx separation of 4m and both placed at 1.5m depth from surface water level is shown in the Fig.1. The acoustic transducers used were directional with a beam width of 90°. The top waveform in Fig.1 is the transmitted impulse signal and the bottom waveform is the corresponding response. It can be well-approximated as a one-sided exponential power delay profile commonly encountered in RF channels. The average and rms delay spread are the same for exponentially distributed power delay profiles [6] and in this case it is approximately 30ms.

The second step was to measure the channel frequency response. We transmitted a maximal length sequence (MLS) of length 2^{18} and estimated the power spectral density of the recorded the signal [7]. The power spectral density gave us an estimate of the channel's magnitude response characteristics which is shown in Fig.2.

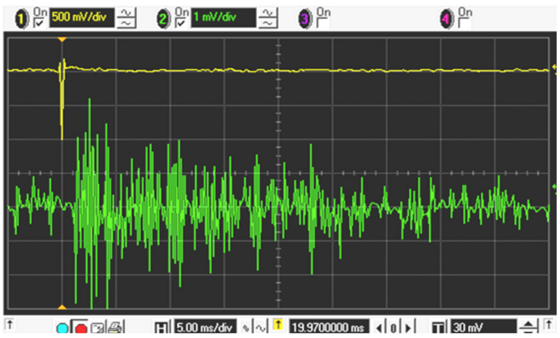

Figure 1. Impulse response of UWA channel: Oscilloscope Measurement (X-axis scale: 5ms/div)

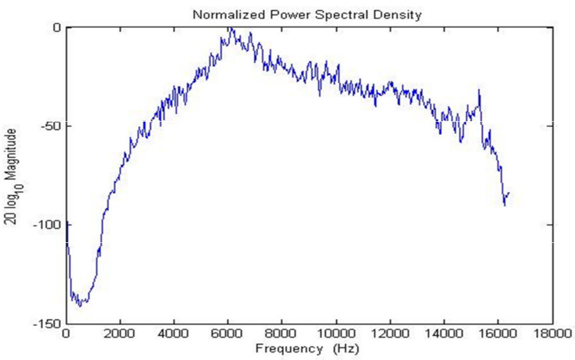

Figure 2. Frequency Response of UWA channel.

This frequency response measurement was carried out in a large acoustic tank (at NPOL Cochin) with a tx-rx separation of 40m and both placed at a depth of 9m from the surface water level using the same acoustic transducers mentioned earlier.

IV. ACOUSTIC MODEM: DESIGN CONSIDERATIONS

As is evident from the previous sections, the underwater acoustic environment is a very noisy, highly attenuating, multipath fading channel with significant Doppler spreads, large number of interference sources, and virtually no support of pulse to pulse correlation. Hence signal processing techniques specifically for the problems arising in this demanding environment are unique. With this perspective, the main points to be considered during the design of such a system are as follows:

A. Single Carrier vs. Multi carrier Modulation Schemes

From Table 1, the coherence bandwidth (delay spread) is seen to limit the number of symbols transmitted per second. Multi carrier modulation schemes such as OFDM can effectively transform the frequency selective fading channel into multiple parallel flat fading channels without requiring knowledge of channel gains at the transmitter. Depending upon the worst case delay spread encountered in the channel the length cyclic prefix/zero prefix can be adjusted in OFDM-based systems. This approach is much simpler than single carrier modulation approaches with prohibitively complex adaptive equalization requirement for UWA channel.

B. Coherent Detection vs. Differential Detection

For coherent detection, the path gains must be known at the receiver which is referred to in literature as Channel State Information at the Receiver (CSIR). In practice, the path gains are estimated at the receiver by transmitting pilot signals which causes reduction in the effective data rate. There will be mismatch between the path gains and their estimates and it is almost impractical to track the variations for very fast fading channels such as UWA channels. In differential detection, the decoder does not need channel estimation (no CSIR). The transmitted symbols depend on each other and the decoder can detect from successive symbols.

C. Time Domain Differential OFDM vs. Frequency Domain Differential OFDM

In OFDM, differential modulations can be applied either in time domain (between successive OFDM symbols on the same sub carrier) or in frequency domain (between adjacent sub carriers in the same OFDM symbol). If the fading is not frequency selective, frequency domain differential OFDM performs well because of good coherence between sub carriers even under fast fading (high Doppler). Similarly, if the fading is not fast (low Doppler), time domain differential OFDM performs well because of good coherence between adjacent OFDM symbols, even under frequency selective fading (large RMS delay spread). So in the most general case, neither technique provides any benefit for underwater acoustic channels, because the fading phenomenon is both frequency selective and fast. However if the relative velocity between platforms is slow to moderate (low Doppler), time domain differential OFDM is a good choice as against coherent techniques.

D. *Single Differential vs. Double Differential Schemes*

In the previous section, we have seen that time domain differential technique is a good choice for UWA channels provided Doppler is low (slow fading). This is due to the well-known fact that DPSK/DQPSK eliminates the performance degradation due to phase differences between the carrier signal and the receiver's local reference signal if the differences are constant over two symbol intervals; however, it does not eliminate degradation due to frequency differences/offsets.

In the late 1970's, several modulation schemes were proposed [8,9] that employed second-order differential encoding of the data, i.e**.**, encoding the data into the signal phase as the difference of two adjacent phase angle differences, thereby requiring three symbol intervals for decoding. Such modulation schemes, together with second-order differentially coherent detection, can be shown to reduce the effects on performance degradation due to both phase and frequency differences when the differences are constant over three symbol intervals. Such systems were referred to by Pent [8] as "Doubly Differential PSK (DDPSK)." This modulation technique was first introduced in Russian literature for high Doppler, Low Earth Orbit (LEO) satellite communication applications. DDPSK/DDQPSK along with OFDM can be applied for high Doppler UWA applications under moderate to high SNR conditions. It has been shown [10] that a 2dB SNR advantage over classical DDPSK can be obtained by choosing a delay of 2T rather than T in the first stage of the encoder and the second stage of the decoder under AWGN scenario.

E. *Single/Double Differential Space-Time Coding for Transmit Diversity*

Space-time codes such as Alamouti codes provide transmit diversity with only linear processing complexity at the receiver. Differential STBC schemes with two or more [11] transmit antennas have been proposed for flat fading channels. The advantage of differential schemes is that they do not require CSIR. Diggavi et al [12] combines this form of differential coding with OFDM for signal transmission over frequency selective fading channels. Generalizing single-antenna double differential coding ideas to space–time context, Double Differential Space–Time Block Codes (DDSTBC) for Time-Selective Fading Channels have been developed [13]. DDSTBC can recover the information symbols with antenna diversity gains without estimating the channel at the receiver regardless of frequency offsets, hence is suitable for UWA applications.

F. *Interleaving and Error Control Coding*

The fading phenomena in channels cause burst error in communications which are extremely difficult to control. The solution is to convert the burst error into random error through effective interleaving. The channel coherence time must be taken into account for the same. An error control coding technique should be used along with this so that random errors can be detected and corrected effectively. Convolutional error coding schemes along with Viterbi decoding are the usual choices for random error mitigation schemes.

V. SYNCHRONIZATION ISSUES

The success or failure of any wireless digital communication system depends on the symbol synchronization between the receiver and transmitter. There are not one but three seemingly different problems that have to be solved. They are 1) Symbol synchronization, 2) Doppler Offset Compensation and 3) Sampling Skew Correction between the transmitter and receiver. An interesting fact is that all the above mentioned problems can be solved at a single step using a very innovative and computationally efficient approach: that of resampling the original signal [14]. The reason for the same is that for a broadband signal, the sampling skew manifests itself as a scaling in time. The received Doppler affected signal can be expressed as

$$r(t) = s[(1 + a)t] \tag{1}$$

where s(t) is the transmitted signal, r(t) is the received Doppler affected signal and 'a' is the waveform time compression or expansion factor for a moving terminal with speed v (a = v/c). The signal can be either compressed or elongated in time depending on the sign of a. If we consider a sampled signal $s[nT_s]$, where n is the sample index and T_s is the sampling period, the Doppler in the received signal is equivalent to a scaling of the sampling period.

$$r(t) = s[n(1 + a)Ts] \tag{2}$$

Signal is scaled in time by (1+a), so that a transmitted pulse of duration T is observed at the receiver as having duration T/(1+a). It can be verified that [15] this signal is distorted two ways in the frequency domain: Firstly, the bandwidth B is observed as (1+a)B. Secondly, a frequency offset af_c is introduced. The first type of distortion accounts for motion-induced Doppler spreading, while the second accounts for Doppler shifting. The first effect can be often neglected in RF systems. Non-negligible motion-induced Doppler spreading thus emerges as another major factor that distinguishes an acoustic channel from the mobile radio channel, and dictates the need for explicit delay synchronization in all but stationary systems [15].

There is another major difference in RF and acoustic multicarrier systems. Since most of the RF systems are narrowband, the Doppler shift appears as almost equal for all subcarriers. This fact greatly eases the task of synchronization, and many efficient synchronization algorithms have been developed for OFDM radio systems. In a wideband system, the situation is quite different. Here, each frequency f_k is shifted by an amount that cannot be approximated as equal for all subcarriers. Thus Doppler Effect in a wideband acoustic system causes non-uniform frequency shifting. A comparison of OFDM parameters in Underwater Acoustic with Wireless LAN [16] and UWB-OFDM [17] systems are given in Table II

If the amount of time scale 'a' is known, then the received signal can be compensated by an inverse time scaling. In a multi-rate discrete time processing parlance, this is equivalent to resampling the signal by a factor (1 + a). The compensated signal can be expressed as

$$s_{comp}[nT_s] = r\left[\left(\frac{n}{1+a}\right)T_s\right] \quad (3)$$

The objective is twofold: the first being to estimate the amount of time scaling/resampling factor (1+a) occurred and then the second to compensate for the same using a resampling operation. The frame structure of the transmitted data frame is modified to cater to this technique as in Fig. 3. The OFDM symbols are concatenated along with their cyclic prefixes and are transmitted as one frame. Frame sync (Linear FM waveform) is appended at the beginning and the end of the frame as illustrated in Fig. 3. There is a single matched filter at the receiver corresponding to the frame sync.

TABLE-II
COMPARISON OF OFDM PARAMETERS IN UNDERWATER ACOUSTIC, RADIO, AND UWB CHANNELS

	Experiments for this paper	Wireless LAN	UWB OFDM
Propagation speed, c	1500 m/s	3×10^8 m/s	3×10^8 m/s
Bandwidth, B	6 kHz	20 MHz	528 MHz
Carrier Freq f_c	8 kHz	5.2 GHz	3 – 10 GHz Freq Hopping
Narrowband or Wideband?	$B/f_c = 0.75$ Wideband	$B/f_c=0.0038 \ll 1$ Narrowband	B > 500MHz Wideband
Time scale factor (a = v/c)	$a=1.3\times10^{-3}$ for v = 2m/s	$a = 7\times10^{-8}$ for v = 20m/s	$a = 7\times10^{-9}$ for v = 2 m/s
Typical multipath spread	10-300 ms	~ 500 ns	~ 100 ns
Typical coherence time	~ 1 s	~ 5 ms	~ 2 ms
one OFDM symbol duration	48 – 352ms	4µs	0.3µs

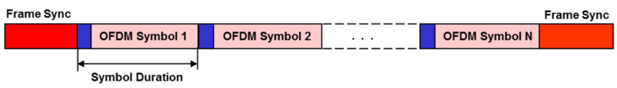

Figure 3. Modified Frame Structure for Timing Synchronization

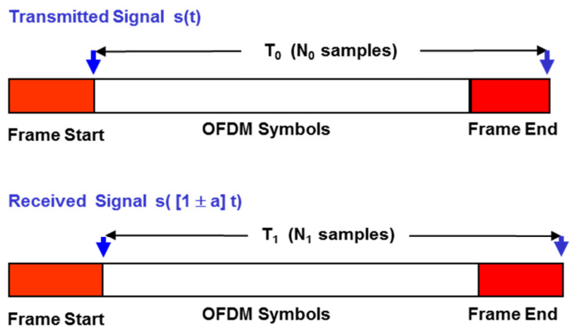

Figure 4. Change in Frame Length due to Time Scaling by Doppler

The duration of the received frame T_1 is measured at the receiver by calculating the time index difference between the matched filter output maximum corresponding to the frame sync waveform at the beginning and the end of the received frame. If T_0 is the duration of the transmitted frame, then the scaling/Doppler parameter (a) is given by (Fig. 4)

$$a = \frac{T_1}{T_0} = \frac{N_1}{N_0} \quad (4)$$

The target movement in the time duration between the frame sync headers causes the time scaling effect. This observation is going to play a very crucial role in the choice of the waveform for the frame sync pulses. The notion of two independent measurements is very critical and necessary. Since the measurements are independent, the variances will add up in the estimation of T_1. The Cramer Rao lower bound for the estimate $\widehat{T}_1$ is thus given by [18]

$$\mathrm{var}(\widehat{T}_1) \geq \frac{2}{\left(\frac{\epsilon}{N_0/2}\right)B} \quad (5)$$

where ϵ is the energy of the signal and B is the bandwidth. The CRLB expression gives the first impression that no matter how different the signals are, if their bandwidths are the same, a good estimate is possible. By studying the ambiguity diagram of different waveforms having same bandwidth and pulse energy [18], we can see that the frame sync pulse signals used should have the following properties.

- High time delay resolution.
- High Doppler tolerance.

The first property is needed since the estimation method essentially measures scaling in time delay of the received frame. The second property is required since the matched filter designed for the transmitted waveform must able to effectively detect the Doppler shifted version of the same to identify the time index accurately. The LFM signal has the unique property in that it can be tuned to have adjustable delay resolution and Doppler tolerance at the same time. This can be done by decreasing the pulse width (for increasing the delay resolution) and by increasing the bandwidth (for increasing the Doppler tolerance) independently. This is manifested as an increased slope in the ambiguity plane [18]. We can safely conclude that the LFM waveform with high slope in the ambiguity plane is an ideal candidate for the estimation of time scaling/resampling factor.

The relative velocity between the transmitter and receiver platforms decides how often Doppler estimation/correction should be done. The immediate implication for our design is the limitation in the maximum frame size that can be used. If the relative velocity is changing rapidly (ie, presence of acceleration), the frame size should be reduced to provide faster rate of Doppler correction. Another important assumption in our design is that all paths have same Doppler rate or one of the paths is dominant.

A. Effect of Symbol Synchronization

We measured the resample factor (shift in the length between the frame sync waveforms at the start and end of a frame) due to the sampling skew between the transmitter and receiver. The correct estimate of the resample factor is 10021 (which is to be interpreted as a shift of 21 samples relative to 10000 samples) which is computed as

$$\text{Resampling Factor (RF)} = \frac{T_1}{T_0} \times 10000 \qquad (6)$$

where T_1 is the number of samples between the chirps measured at the receiver and T_0 is the original number of samples between the chirps as indicated in Fig. 4. In order to study the effect of symbol synchronization, we varied this parameter at the receiver in the range of 18 to 24 samples relative to 10000 samples. The SNR parameters and the cyclic prefix length (matched to the delay spread in the test bed) were kept constant during the experiment. The decoding trellis depth was also kept constant at 150. The result of the variation in the symbol synchronization parameter is illustrated in Fig. 5(a) to 5(g). It is seen that even a slight change in the symbol synchronization affects the overall performance of the communication system. This experiment has helped us to understand the criticality of the symbol synchronization with respect to system performance.

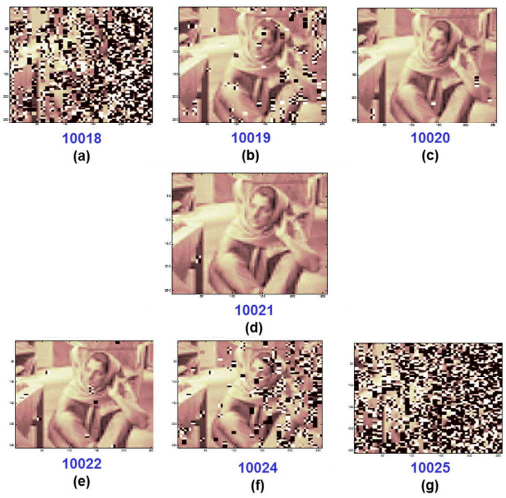

Figure 5. Effect of Loss in Synchronization: Visual Illustration

VI. CONCLUSIONS AND FUTURE WORK

We could successfully demonstrate underwater communication with data rate up to 5.4 kbps (after rate R= ½ convolutional coding) using 6 kHz bandwidth with DQPSK over OFDM [1, 2]. The range performance is heavily dependent upon the operating environment. The system can support mobility up to ±3m/s with the help of Doppler compensation by resampling technique described in this paper. The focus of future research will be to improve the robustness of the system by several key techniques outlined in this paper such as 1) Transmit Diversity techniques to compensate for severe fading 2) Modulation techniques which are inherently tolerant to Doppler 3) Synchronization under high Doppler, which is peculiar to UWA channels.

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