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Research Article

Investigation of Channel Modeling and Simulation of OFDM Based Communication Near Northern Regions of Arabian Sea

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Abstract: Wideband nature of oceanic channel when dealing with multicarrier acoustic subcarriers introduces severe Doppler shifts, little variations may cause overlapping of subcarriers such that entire signal can get completely distorted. Therefore, one of the major problems in OFDM based underwater acoustic communication is the sensitive nature of wideband acoustic subcarriers. In this study, Bellhop beam tracing is used to model two regions in the north of Arabian Sea and the two-step receiver algorithm is used over these channel models. Multipath with delay channel model is obtained using the Bellhop ray tracing algorithm while random Doppler shift is induced in MATLAB on each block and also in the complete OFDM packet. In the first step, resembling converts a wideband problem in to narrowband problem and in the second step; high resolution Carrier Offset Frequency (CFO) tracking compensates the residual Doppler. Cyclic Prefix (CP) OFDM scheme based on block-by-block processing is deliberated here for fast varying channel. In the proposed algorithm, null subcarriers are facilitated for Doppler removal while pilot bits are used for Least Square (LS) channel estimation. Simulation on MATLAB is carried out on both channels, i.e., near Gawadar Coast and Karachi Harbor; satisfactory results are achieved in terms Low Bit Error Rates (BER) even in high relative speed between transmitter and receiver. These results further suggested and make convinced for the experimental test/ trials, specifically in the region of north Arabian Sea.

Keywords: Bellhop, Cyclic Prefix (CP), doppler shift, OFDM, Underwater Acoustic Communication (UWAC)

INTRODUCTION

In this study, we will investigate the two major problems caused by underwater channel (i.e., effects of multi-paths and non-uniform Doppler Shift) for the reliable design of Underwater Acoustic Communication (UWAC) system. Underwater acoustic channel has very strong multipath effect due to the higher probability of reflections from wavy sea surface, uneven sea bottoms and other obstacles. The transmitted signal reflected several times before reaching to the receiver such that many delayed replicas of the same signal are also received that cause destruction of original signal in terms of Inter-Symbolic Interference (ISI). Longer the channel time delay will cause more ISI and this delay is much more dominant in underwater channel as compared to RF channels. In order to avoid this destruction of the signal, multicarrier schemes have been analyzed for UWAC and OFDM is found to be best suited candidate. In OFDM, Cyclic Prefix (CP) and Zero Padded (ZP) schemes have been used successfully in many researches to mitigate the effects of strong multipath. In (Kang and Litis, 2008; Nasri *et al*., 2009; Chitre *et al*., 2005), the authors have used CP concept and found it very promising and effective to minimize the effect of ISI by converting linear convolution problem to circular convolution problem that can be handled through low complex equalization. However, due to the more power requirement which is not suitable for underwater modems, padding of zero bits instead of repetition of the message signal has been efficiently utilized in Li *et al*. (2008), Wang *et al*. (2010) and Parrish *et al*. (2008).

OFDM based underwater communication system is very sensitive to the frequency offset due to its wideband nature, little shift may cause overlapping of subcarriers such that entire signal can get completely distorted. Another reason is the slower speed of sound in water as compared to RF communication that causes oceanic dynamics more dominant and that may cause Doppler shifting in the signal in the form of subcarriers overlapping. This type of overlapping is termed as Inter-Carrier Interference (ICI) that is the major problem in OFDM based underwater communication systems; it can damage the orthogonality between the subcarriers. To minimize the effect of Doppler shifts, several schemes have been developed in recent time. Stojanovic (2006), for compensation of non-uniform Doppler shifts through pilot tone based phase tracking model, (Li *et al*., 2008), for two step approach and

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Fig. 1: Northern Arabian Sea near costal region of Pakistan

adaptive phase tracking model ink. Tu *et al*. (2009) are specifically considered valued approaches.

About Arabian Sea: We have selected two-channel models in the Arabian Sea for the simulation and analysis of our scheme of OFDM based UWAC. The Arabian Sea is a region of the Indian Ocean bounded on the north by Pakistan and Iran, Fig. 1 on the south by northeastern Somalia, on the east by India and on the west by the Arabian Peninsula. Pakistan's coastline on the Arabian Sea is in a central position for trading by sea both with South Asia and the Far East and beyond and with the Middle East to the west. The maximum depth of Arabian Sea near Pakistan's coastline is about 700 m and mostly occupied with sandy and rocky bottom profile. Using bellhop, aquatic channel models near harbor of Karachi and coast of Gawadar are developed here with the aim to study the complexities of this oceanic region and accordingly workout for the suitable communication techniques.

Bellhop ray tracing program and channel model: In order to perform two-dimensional acoustic ray tracing for sound speed profiles of UWA channels in Arabian Sea, a highly efficient Bellhop ray tracing program is used. Using MATALB program, Bellhop.exe (i.e., based on the theory of Gaussian beam) is executed that outputs the travel time and amplitudes of the multiple paths reflected from surface and bottom boundaries of the ocean. Porter (2011) and Rodrguez (2008) further explain the importance of Bellhop ray tracing algorithm pertinent to the provision of other parameters like ray coordinates, Eigen-rays and transmission loss (coherent, incoherent or semi-coherent). Multipath induced models of these channels together with spar sing function are further utilized for the designing of robust UWAC.

About OFDM: UWA channels being both frequency and time selective, pose great challenges for the designing of high rate underwater acoustic communication. Many existing techniques used at radio frequencies do not work in the hostile UWA channel. However, multicarrier modulation in the form of Orthogonal Frequency Division Multiplexing (OFDM) has proven robust and best suited in underwater environment because it offers low complexity design of receivers that can deal with highly dispersive channels. In, OFDM system, the available bandwidth is divided into several sub-carriers. The frequency spacing of the carriers is chosen in such a way that the modulated carriers are orthogonal and do not interfere with one another. The dominant effects of multipath spread and respective inter-symbolic Interference in UWA channel can be properly mitigated with OFDM based communication. However, wideband nature of acoustic communication with random temporal and spatial variation of sea introduces motion induced Doppler distortion with frequency offsets, significantly different at different frequencies. This problem of carrier frequency offsets can destroy orthogonality of the subcarriers in OFDM based communication and will lead to severe Inter Carrier Interference (ICI).

It is therefore, in recent research, methodology for the reliable detection of OFDM signal received from Doppler distorted and time varying channels are being investigated. Thus in order to handle the Doppler distortions in selected locations of Arabian Sea; we have also modeled Doppler Effect as a change in the time scale of the transmitted waveforms. In receiver side, we get Doppler induced multiple paths possessing varying amplitudes depending upon the arrival times from the surface and bottom reflections of the chosen channels.

About receiver algorithm: The receiver algorithm we are presenting here is based on the preamble and post-amble of a packet consisting of multiple OFDM blocks to estimate the resampling factor as used in (reference Milica). The null subcarriers will provide the means for the compensation of high resolution residual Doppler and the pilot subcarriers will facilitate the channel estimation. The proposed receiver design is suitable for fast varying UWA channels as it relies on block-by-block processing and doesn't depend on channel's coherency among the OFDM blocks. To test our scheme, simulation work on MATLAB were carried out on two different channels models (i.e., Karachi Harbor with range 7 Km and Gawadar coastline with range of 10 Km) of Arabian Sea. Using OFDM block of 256 subcarriers, data rates of 3.4 to 3.8 kbps are achieved for selected channel models with QPSK modulation and rate 1/2 convolution coding. The frequency bands of 6 KHz centered at 7 KHz were selected for both channel models and satisfactory results are achieved even with one receiving element.

The next sections of this study are ordered as follows: In section 2, generations of channel models in Arabian Sea are explained. The performance of a conventional OFDM receiver and proposed approach to

Fig. 2: Channel model near Gawadar coast (Pakistan)

Fig. 3: Channel model near Karachi harbor (Pakistan)

mitigate the Doppler shift are covered in section 3 and 4, respectively. Performance results for the simulation of selected channels are discussed in section 5 and 6. Finally, we draw the main conclusions in section 7.

GENERATION OF CHANNEL MODELS IN ARABIAN SEA

In this study, 2 UWA channels coordinates in the Northern-West Arabian Sea are considered with the aim to learn and explore the suitable method of communication initially using MATLAB Simulation. Using Google Earth software, following desired locations are found w.r.t. the depth profiles, bathymetry and range:

Coast of Gawadar: 25°01'42.39" N, 62°24'44.19" E and 25°01'42.68" N, 62°30'43.53" E near the Gawadar Port. The Gwadar Port is a warm-water, deep-sea port situated at Gwadar in Balochistan, Pakistan at the apex of the Arabian Sea and at the entrance of the Persian Gulf, about 460 km west of Karachi and approximately 75 km (47 mi) east of Pakistan's border with Iran. The sloping bottoms and intermediate depths near Gawadar coast make this region difficult for the sound propagation and may offer very complicated channel for underwater acoustic communication. The average depth of this region is 350 m and sea water is also warm in nature that makes marine life ideal for their existence. Impulsive noise of snapping shrimp may also be the dominant part of degradation for this oceanic channel; however, in proposed communication system we will not cater the minimization step for this non-linear noise. In Fig. 2, bottom profile of the selected UWA range with respect to the sea floor is shown. The average depth of this sloping range is 221 m with depth deviation of 52 m. In short, UWA channel near Gawadar coast may offer many obstacles, like strong multipath, non-linear noise, etc., against any underwater acoustic communication system.

Coast of Karachi: 24°20'00.16" N, 66°26'42.27" E and 24°22'43.72" N, 66°23'46.50" E near the harbor of Karachi. The Karachi (Latitude: 24°50'6" N Longitude: 66°58'40" E), natural harbor was once known as the gateway to Asia, due to its strategic geographical location and an important warm water port also serves as a refueling stop for ships. The bottom profile is almost flat and average floor depth is around 100 m near the coastal region of Karachi. Figure 3 shows the elevation profile of selected UWA shallow channel near Karachi coast. Depth profile revealed that selected range is almost flat with the variation of only 11 m. Due to heavily engaged sea traffic near coastal region of Karachi, proposed channel may be assumed as extremely complex shallow water channel. This heavily noisy channel may also offer strong Doppler shifts and great multipath effect for any underwater acoustic communication.

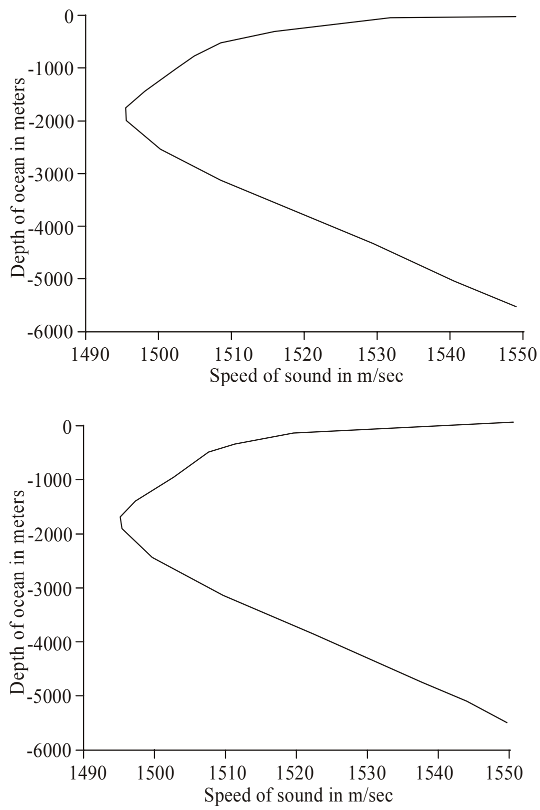

Fig. 4: Sound speed profile (up) Gawader (below) Karachi

From the above mentioned channel models, Bathymetry files are also made for the subsequent use during the calculation of channel impulse and frequency response.

Generation of ENV files from data given by world ocean atlas: From the data base provided by World Ocean Atlas at 1-degree resolution and extended depth of 5500 m, sound speed profiles on the coordinates of selected channel region are obtained. In (reference WOA), relevant details are mentioned. Figure 4 shows the obtained SSPs of selected regions. Cubic-spline interpolation in MATLAB is used to acquire the high desired resolution of SSPs at the location of our interest. Accordingly, generation of Environmental Files (ENV) are carried out that includes maximum floor depth, the depths of source (transmitter) and collector (receiver), range and the number of beams to be transmitted. These ENV files is further used to the find the channel impulse and frequency response using Bellhop ray tracing method.

Using bellhop to generate channel models in Arabian Sea: MATLAB program is written to run Bellhop.exe that needs number of beams to be transmitted to test channel behavior. Beam tracing is similar in principle to ray tracing but only considers the paths of finite width beams rather than infinitesimal width rays. Using Gaussian intensity profile or geometric beams, Bellhop beam tracing program can produce the same result as a standard ray trace. In order to find channel impulse response, propagation time and amplitudes of the multiple paths are obtained that explains the reflection phenomena from the surface and bottom boundaries of the ocean. Each path of any acoustic channel can be assumed to act like a low pass filter and hence the overall impulse response can be written as:

$$h(\tau, t) = \sum_{p=0}^{K} h_p(t)\delta\big(t - \tau_p(t)\big)$$

where,
h_P (t) : The time varying path gain
τ_p : The path delay of the P^{th} path

If some of the coefficients h_P (t) are zero or relatively very small, the corresponding estimates can (and should) be discarded. By doing so, the problem of dimensionality is reduced to the one dictated by the physics of propagation and not by the number of subcarriers. Out of the *K*, *J* coefficients are selected as those whose magnitude is greater than some threshold. Hence, sparse channel impulse response h_s (t) is obtained optimally by truncation in magnitude.

$$h_s(\tau, t) = \sum_{p=0}^{J} h_p(t)\delta\left(t - \tau_p(t)\right) \quad (1)$$

Channel sparsing in terms of significant amplitudes of the paths is also considered in our program to avoid infinitesimal amplitudes beams. Channel sparsing will be utilized as important tool in the later stage i.e., UWAC. Both channel vectors obtained from bellhop beam tracing program are further used in the simulation of OFDM based communication. Original and sparse channel impulse responses of the selected flat region near Karachi Harbor are shown in Fig. 5 and 6, respectively. Considering original channel impulse, various paths of the beams can be clearly observed that makes the channel more complex and resistant against any UWAC. On the other hand, sparse channel reduces the complexities of channel by avoiding insignificant amplitudes and consideration is only given on those multi-paths whose magnitudes are greater and equal to the half of the maximum amplitude pulse. Sparse channel model is used in our proposed OFDM based UWAC system.

Similarly, original and sparse channel impulse response obtained from the Bellhop beam tracing program are shown in Fig. 7 and 8, respectively. Difficult sloping region of Gawadar coast can be correctly explained from its complex channel impulse response.

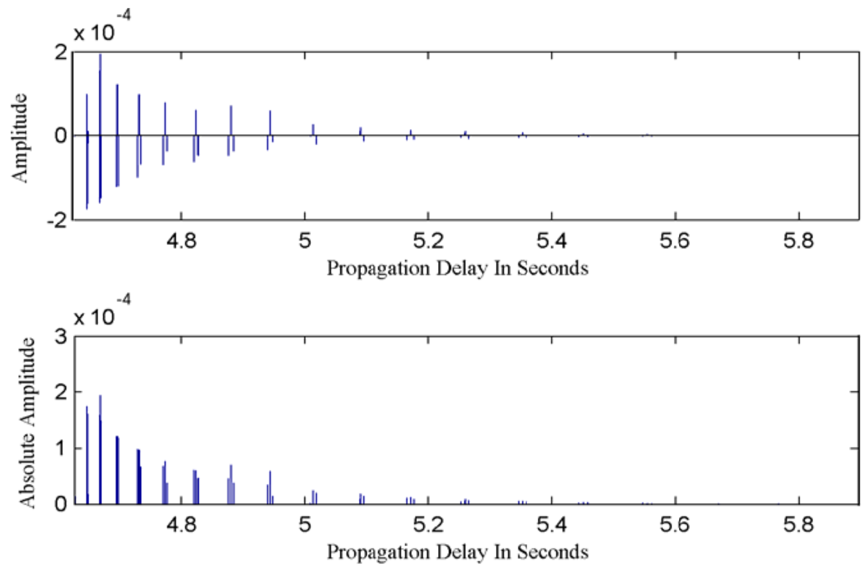

Fig. 5: Original channel model near Karachi (up) impulse response (below) absolute value

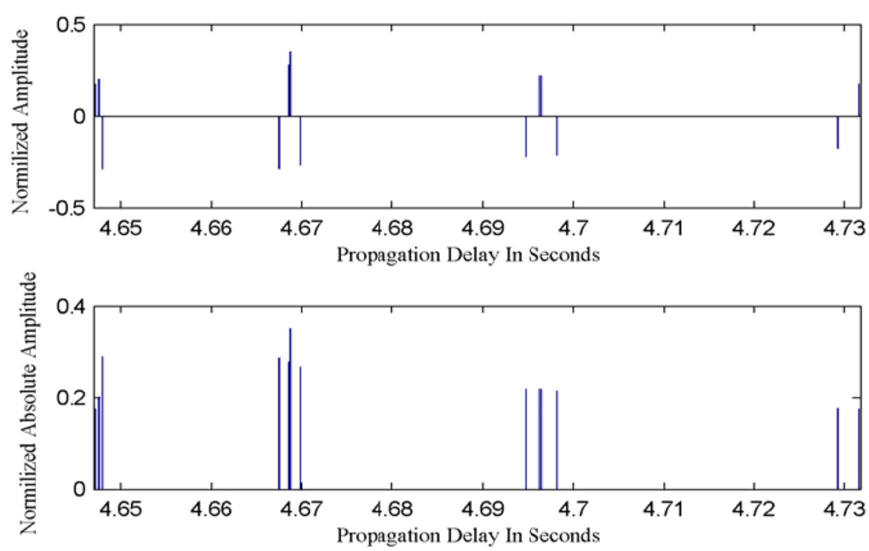

Fig. 6: Sparse channel model near Karachi (up) impulse response (below) absolute value

In Fig. 8, deletion of many unwanted paths is clearly viewed that makes this channel more ideal for OFDM based communication even in the presence of non-uniform Doppler distortions and high noise activities.

OFDM BASED COMMUNICATION SCHEME FOR MODELED CHANNELS

In the proposed OFDM based scheme, let T and T_g symbolize the symbol time and guard interval respectively. The total OFDM block can be written as:

$$T_{total} = T + T_g$$

The frequency of the subcarrier is $\Delta f = \frac{1}{T}$ and the k^{th} subcarrier frequency is written as:

$$f_k = f_c + k\Delta f, k = -K/2, \dots, \dots, \dots, K/2 - 1 \quad (2)$$

where,

f_c : Carrier frequency
K : The total number of subcarriers used in OFDM based communication

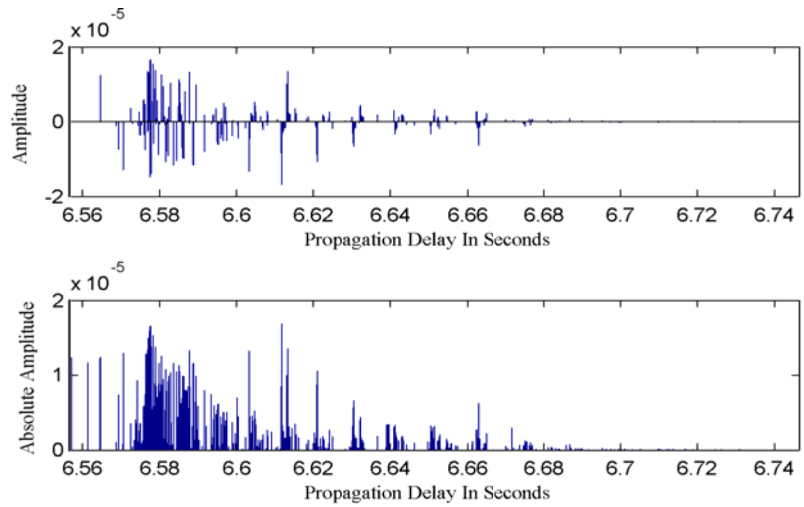

Fig. 7: Actual channel model near Gawadar (up) impulse response (below) absolute value

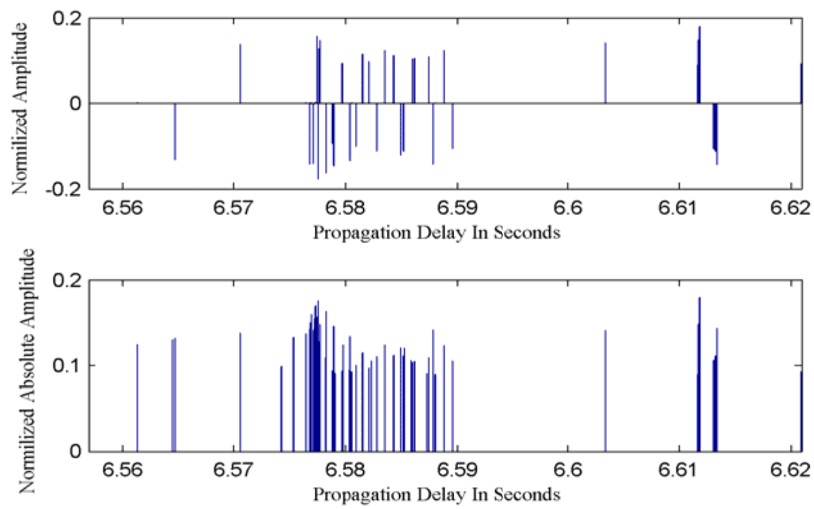

Fig. 8: Sparse channel model near Gawadar (up) impulse response (below) absolute value

Bandwidth B.W. is in relation with K as $\text{B. W.} = \frac{K}{T} = K\,\Delta f$ inversely, from bandwidth we can derive, $\Delta f = \frac{\text{B.W.}}{K}$

Let us consider one Cyclic Prefix (CP) OFDM block. Let d[k], denotes the information symbol to be transmitted on k^{th} subcarrier. The non-overlapping sets of active subcarriers K_A and null subcarriers K_N satisfy

$$K_A \cup K_N = \{-K/2, \dots, \dots, \dots, K/2 - 1\}$$

where,
$K_A = K_S + K_P$, K_S is a set of information bits
K_P = The number of pilot bits per symbol

The transmitting signal in pass-band can be written as:

$$s(t) = s_a(t) + s_g(t)$$

where, $s_a(t) = \mathrm{Re}\left\{\sum_{k\in K_N}\left[d[k]e^{i2\pi k\frac{t}{T_{total}}}\right]e^{i2\pi f_c t}\right\}$, for $t \in \{0, T\}$ is the expression for OFDM symbol.

whereas: $s_{g(t)} = \mathrm{Re}\left\{\sum_{k\in K_N}\left[d[k]e^{i2\pi k\frac{t}{T_{total}}}\right]e^{i2\pi f_c t}\right\}$ for $t \in \{T - T_g, T\}$, represents transmitting signal during guard interval time.

So, we can write complete expression for transmitting signal as:

$$s(t) = \mathrm{Re}\left\{\sum_{k\in K_N}\left[d[k]e^{i2\pi k\frac{t}{T_{total}}}\right]e^{i2\pi f_c t}\right\}$$

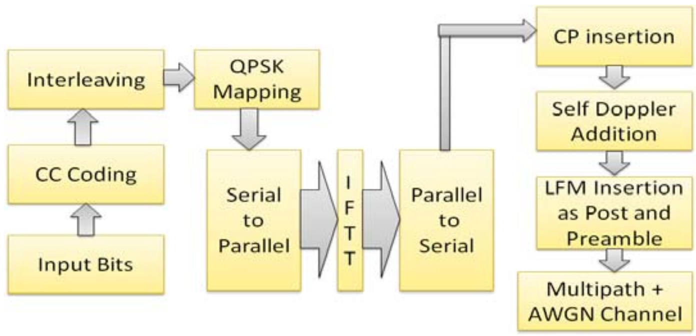

Fig. 9: Block diagram of OFDM transmitter

for

$$t \in \{0, T\} + t \in \{T - T_g, T\} \quad (3)$$

Doppler factor and addition of Doppler in transmitting signal: From (1), if h_P (t) is the path amplitude and τ_p (t) is the time varying path delay we make following assumption for our receiver algorithm:

- For all paths have a same Doppler scaling factor α such that:

$$\tau_p(t) = \tau_p - at$$

Depending upon the oceanic fluctuations, Doppler scaling factor could be different for different paths. As explained in reference (malice's study), the proposed method is also based on the assumption that all paths have the same Doppler scaling factor. This assumption is important as useful signals could increase the overall noise variance considerably. However, Doppler shifts are randomly generated and added in all symbols and also on the complete packet to show how much deviation is produced between source and receiving points. The same is compensated using proposed algorithm which further witnesses the relative motion/fluctuations in terms of Carrier Frequency Offset (CFO).

- τ_p, h_P (t) and α are constant over 1 symbol time T_{total} but different for other symbols.

From above two assumptions, it is revealed that due to Doppler distortion, each path is scaled in duration from T_{total} to $T_{total}/(1+a)$, such that Doppler induced transmitted without multipath can be modeled for our simulation work as:

$$s_{Doppler}(t) = \mathrm{Re}\left\{\sum_{k \in K_A} \left[d[k]e^{i2\pi k\Delta f t(1+a)}\right]e^{i2\pi f_c t(1+a)}\right\}$$

for

$$t \in \{0, T\} + t \in \{T - T_g, T\}$$

After multipath sparse channel with gain h_P, the receiving signal in baseband satisfies $\tilde{z}(t) = \mathrm{Re}\{z(t)e^{i2\pi f_c t}\}$ and can be written as:

$$z(t) = \sum_{k \in K_A}\{[d[k]e^{i2\pi k\Delta f t} \times e^{i2\pi a f_k t}] \times [\sum_{p=0}^{J} h_p e^{-i2\pi f_k \tau_p}\delta(t + at - \tau_p)]\} + n(t) \quad (4)$$

where,
$\tilde{z}(t)$: The pass band version of receiving signal
n (t) : Channel noise

In Fig. 9, block diagram of considered model of OFDM transmitter is shown.

Receiver design:

Removal of Doppler shifts using a two-step approach: A two-step approach is adopted here to negate frequency-dependent Doppler shifts due to fast-varying underwater acoustic channels:

- Resampling of the received pass band signal is performed for the compensation of non-uniform Doppler. Resampling with appropriate resampling factor rescales the waveforms and introduces frequency-dependent Doppler compensation. Resampling will transform 'wideband' problem into a 'narrowband' problem. The resampling parameter ***b*** should be selected such that:

$$\frac{1+a}{1+b} \approx 1$$

- Resampling of pass band signal $\tilde{z}(t)$ gives $\tilde{y}(t)$ as $\tilde{y}(t) = \tilde{z}\left(\frac{t}{1+b}\right)$; this corresponds and satisfies the resampled baseband signal $\tilde{y}(t) = Re\{y(t)e^{i2\pi f_c t}\}$ as:

$$y(t) = e^{i2\pi\frac{a}{1+b}f_c t} \sum_{k\in K_A}\left\{d[k]e^{i2\pi k\Delta f\frac{1+a}{1+b}t} \times \left[\sum_{p=0}^{J} h_p e^{-i2\pi f_k\tau_p}\delta\left(\frac{1+a}{1+b}t-\tau_p\right)\right]\right\} + v(t) \quad (5)$$

After resampling (5) becomes:

$$y(t) \approx e^{i2\pi\frac{a}{1+b}f_c t} \sum_{k\in K_A}\{d[k]e^{i2\pi k\Delta f t} \times \left[\sum_{p=0}^{J} h_p e^{-i2\pi f_k\tau_p}\delta(t-\tau_p)\right]\} + v(t) \quad (6)$$

From (6), we can view the residual Doppler Effect is similar for all subcarriers. Hence, this narrowband expression only has frequency independent Doppler shifts.

Subsequent to resampling step, high resolution uniform compensation on residual Doppler is carried out by modeling it as a CFO. This step corrects the residual Doppler shift finely to the 'narrowband' model and correspondingly used for best ICI reduction. Using a single CFO (ε) per OFDM symbol for Doppler compensation as:

$\varepsilon = \frac{a}{1+b}f_c$ which further used for compensation of $y(t)$ as:

$$e^{-i2\pi\varepsilon t}y(t) = \sum_{k\in K_A}\{d[k]e^{i2\pi k\Delta f t} \times \left[\sum_{p=0}^{J} h_p e^{-i2\pi f_k\tau_p}\delta(t-\tau_p)\right]\} + \tilde{u}(t) \quad (7)$$

where, $u(t) = e^{-i2\pi\varepsilon t}v(t)$, the additive noise component and $t \in \{0, T\} + t \in \{T - T_g, T\}$

For the output of demodulator in the n[th] subcarrier, the compensated version can be written as:

$$y_n = \frac{1}{T}\int_0^T e^{-i2\pi\varepsilon t}y(t)e^{-i2\pi n\Delta f t}dt \approx H(n)d[n] + u(n) \quad (8)$$

where, $H(n) = \sum_{p=0}^{J} h_p e^{-i2\pi f\ \ \tau_p}$ and u (n) is the resultant noise.

Using proper equalization process, de-scaling and de-rotation of the received is carried out to restore the Orthogonality of the subcarriers used in CP-OFDM.

PRACTICAL RECEIVER ALGORITHM

Figure 10 depicts the processing blocks of proposed receiver. The received signals from the multipath channel are directly sampled and all processing is performed on discrete-time entries. Initially resampling is done after synchronization for preamble detection and Doppler course estimation. Subsequent to cyclic prefix removal and downshifting, CFO estimation is carried out in time domain for the removal of residual Doppler. VA (Viterbi Algorithm) decoding and soft (Log-Likelihood Ratio-LLR) decoding schemes are used to analyze the decoded Bit Error Rates (BER).

Estimation of Doppler scaling factor: Estimation of Doppler scaling factor α through resampling parameter b is carried out by cross correlating the received with known LFM sequences of Preamble and Postamble. The resultant resampling parameter is obtained from the time duration of received signal T_{rx} and the known duration of transmitted signal T_{tx} By comparing both time durations, the receiver reveals an idea of expansion or compression that the data packet has undergone. This information can be used to get an estimate of the relative Doppler shift and thus receiver resample's the signal as:

$$b \approx \tilde{a} = 1 - \frac{T_{tx}}{T_{rx}} \quad (9)$$

Estimation of Carrier Frequency Offset (CFO): The null carriers are used to estimate residual CFO for each OFDM symbol within a block. From (6), the expression for received signal after resampling, we collect K + L samples as:

$$\mathbf{y(k)} = [\mathbf{y(0)}, \dots, \dots, \mathbf{y(K+L-1)}]^{\mathbf{T}}$$

where, L + 1 is assumed channels taps in discrete time. As assumed before, the OFDM symbol consists of K_A active carriers and K_N null subcarriers out of a total of K subcarriers. Let us define null subcarrier's vector W_n of size:

$$(\mathbf{K}+\mathbf{L}) \times \mathbf{1} \text{ as } \mathbf{w_n} = [\mathbf{1}, \mathbf{e}^{\mathbf{i2\pi n}/\mathbf{K}}, \dots, \dots, \mathbf{e}^{\mathbf{i2\pi n(K+L-1)}/\mathbf{K}}]^{\mathbf{T}}$$

and $(\mathbf{K}+\mathbf{L}) \times (\mathbf{K}+\mathbf{L})$ diagonal matrix:

$$\mathbf{E(\varepsilon)} = \mathbf{diag}\left(\mathbf{1}, \mathbf{e}^{\mathbf{i2\pi\varepsilon T}/\mathbf{K}}, \dots, \dots, \mathbf{e}^{\mathbf{i2\pi(K+L-1)\varepsilon T}/\mathbf{K}}\right)$$

Matrix $\mathbf{E(\varepsilon)}$ represents CFO component which destroys the orthogonality of subcarriers. To hold the condition of orthogonality we can nullify CFO hypothetically as:

$$w_n^{\mathcal{H}} E^{\mathcal{H}}(\varepsilon)\, y(k) = 0 \quad (10)$$

This fact allows us to define cost function as:

$$Q(\varepsilon) = \sum_{n\in K_N}\sum_{k\in K}\|w_n^{\mathcal{H}} E^{\mathcal{H}}(\varepsilon)\, y(k)\|^2 \quad (11)$$

The correct compensation of CFO will provide ICI free subcarriers hence, residual Doppler can be excreted in this manner from OFDM based UWAC. In order to find estimated CFO ($\hat{\varepsilon}$), 2 dimensional search of the below expression has been made:

$$\hat{\varepsilon} = \text{abs}[\min_{\varepsilon} Q(\varepsilon)] \quad (12)$$

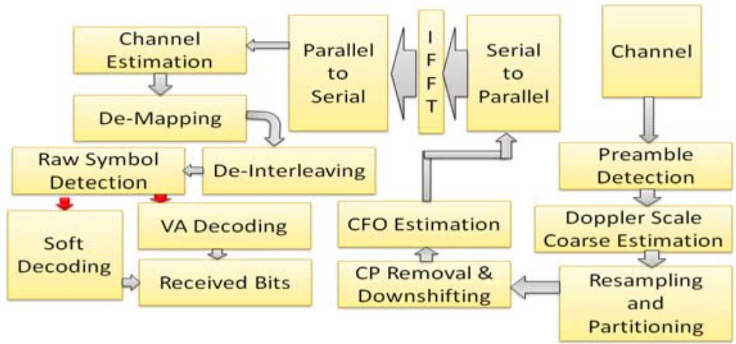

Fig. 10: Block diagram of proposed OFDM-receiver

Table 1: Parameters and respective data rates

Simulation scenario	No. of active subcarriers K_A	Null subcarriers K_N	Data bits rates without coding $\frac{2(K_A - K/4)}{T_{total}}$	With ½ rate CC code	Remarks
Without Doppler	1024	-	8.930 Kbps	4.465 Kbps	$T_g = 341\ ms$
With Doppler	238	18	6.521 Kbps	3.260 Kbps	$T_g = 10.66\ ms$

Pilot tone based channel estimation with relevant mathematical expression: Considering the assumption that Doppler scale factor is constant over one symbol time, ICI will be greatly reduced thru resampling and CFO compensation. Pilot tone based Least Square (LS) method is used here to estimate the channel impulse response. From (8) we can relate the compensated signal at n^{th} subchannel as:

$$y_n = \mathrm{fft}[y(k)]E^{\mathcal{H}}(-\hat{\varepsilon}) = H(n)d[n] + u(n) \quad (13)$$

where,
H(n) : The channel frequency response
u(n) : AWGN

The coefficient of H(n) can be related to the equivalent discrete-time baseband channel parameterized by L + 1 complex-valued coefficients as:

$$H(n) = \sum_{l=0}^{L} h_l e^{i2\pi ln/K} \quad (14)$$

We use K_p pilot symbols as Phase Shift Key (PSK) signals having equal spacing within K subcarriers. Ignoring noise component, the frequency domain channel estimation is carried out by LS method on pilot symbols as:

$$H(p) = \frac{Y_p}{D_p} \quad (15)$$

where, $Y_p = y_n(p)$, $p \in K_p$ and D_P is the known pilot symbols.

Using linear or any suitable method of interpolation, H(n) can be found for all information subcarriers K_S per symbol. Accordingly, data bits for n^{th} sub channel are obtained as:

$$D(n) = \frac{y_n(n)}{H(n)}, n \in K_s \quad (16)$$

PERFORMANCE RESULTS FOR THE SIMULATION NEAR GAWADAR COAST

For simulation of OFDM based UWAC near Gawadar coast, the selected bandwidth is $B.W. = 6$ KHz and the carrier frequency is $f_c = 7$ KHz. CP (Cyclic Prefix) OFDM of 256 subcarriers with the guard interval of $T_g = 10.66$ ms per OFDM blockis used. The subcarrier spacing and OFDM blocks duration are therefore $\Delta f = 23.44$ Hz and $T = 42.7$ ms , respectively. Convolution coding of rate ½ with constraint length of 14 and generator polynomial of (21675, 27123) is applied within the data stream for each OFDM block. The 10 Km channel range is selected with the depths of transmitter and receiver, respectively are 10 and 120 m. Number of equally spaced Pilot and start-end positioned null bits are selected using:

$$K_P = {}^{K}/_{4} = 64 \text{ bits/symbol} \quad \text{and} \quad K_N = {}^{K}/_{18} \approx 18 \text{ bits/symbol}$$

The total number of information (input) bits to be transmitted in an OFDM packet is 1024 that implies into 7 OFDM symbols per packet transmission. QPSK mapping using MATLAB built-in command modem.pskmod and modem.pskdemod is implemented with the aim to obtain the appropriate results. Table 1 shows the detail comparison of data

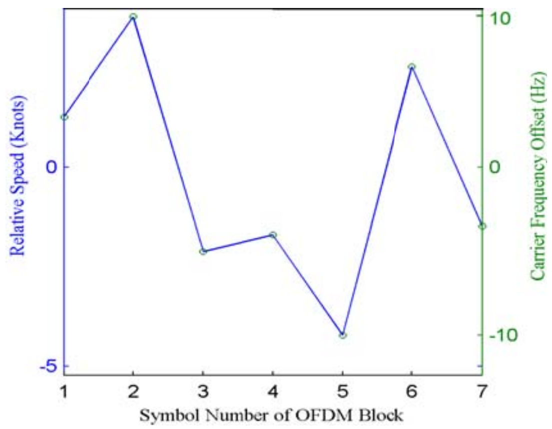

Fig. 11: Tracked CFO and respective relative speeds at 0 dB SNR

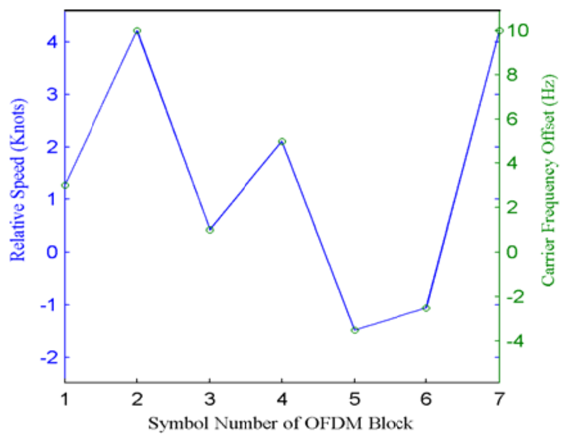

Fig. 12: Tracked CFO and respective relative speeds at 28 dB SNR

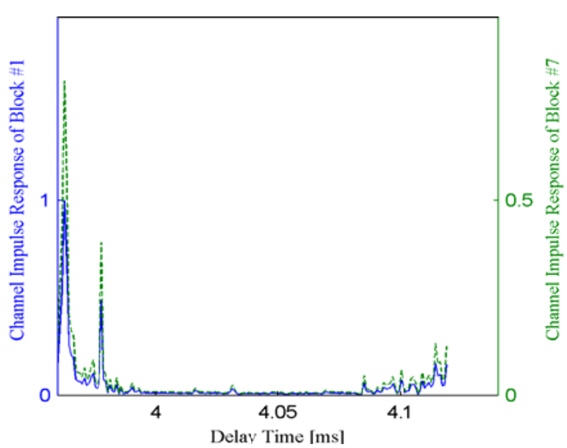

Fig. 13: Channel estimation at OFDM block 1 and 2

rates obtained for the same channel but with and without Doppler distortion.

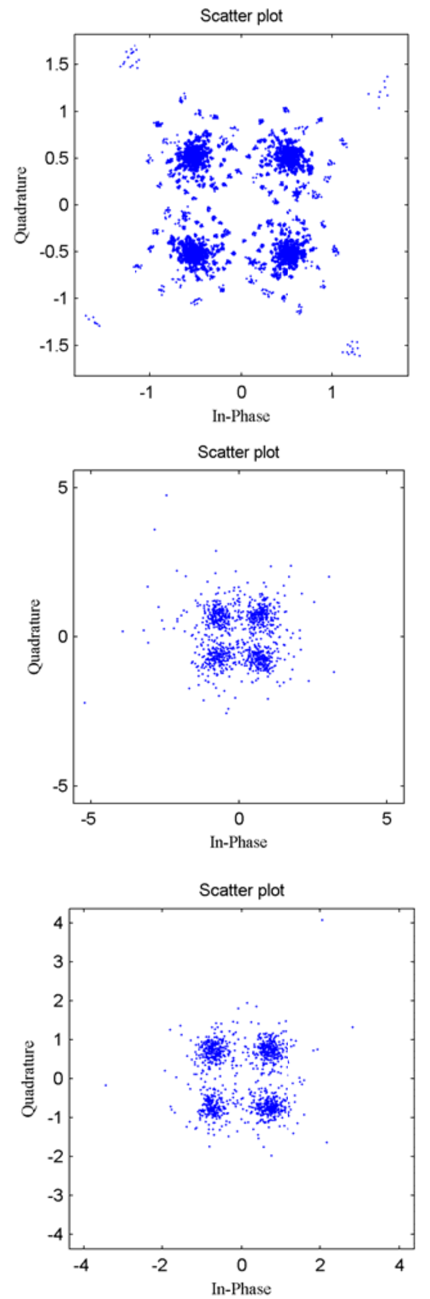

Fig. 14: Scatter plot (up) without doppler (middle) with hard decoding doppler compensation and (below) with soft decoding doppler compensation

Doppler scaling factor estimation: From the environment file near Gawadar coast, the average speed of sound is found to be $\mathbf{V_{sound} = 1520\ m/s}$, so for CFO obtained from the simulation results, the velocity of waves can be calculated as:

$$V_{wave} = \{CFO/(CFO + f_c)\}V_{sound} \times 1.943\ (knots)$$

Figure 11 and 12, respectively explains the results of high resolution C F O tracking obtained from the simulation of proposed receiver algorithm at 28 and 0 dB SNR. When OFDM block 3 is transmitted, frequency offset of 10 Hz i.e., at 4.2 Knote of relative speed is observed this may degrade the performance of the communication system. Thus, fine tuning of CFO is very much essential.

LS channel estimation and symbol detection: Figure 13, shows the estimated channel impulse response at OFDM block 1 and OFDM block 2, minor channel delay of **18 micro sec** is clearly viewed between these 2 paths. Almost same channel energy levels are observed that explain the relative speeds of channel within these OFDM blocks are almost same i.e., relative difference of **1 Knot**.

Scatter Plots of Demodulated (QPSK) receiving bits are shown in Fig. 14 (left to right), respectively for the absence of modeled Doppler, with hard decoding (VA) Doppler compensation and soft decoding (LLR-Log-Likelihood Ratio) Doppler compensation. Response from scattered plots explains that the decision points are more prominent in first case however, for other 2 cases; soft decoding provides little bit better decision capabilities.

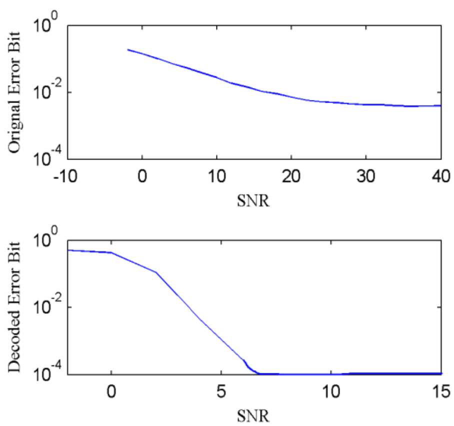

Fig. 15: BER vs SNR (up) raw BER and (down) decoded BER without doppler case

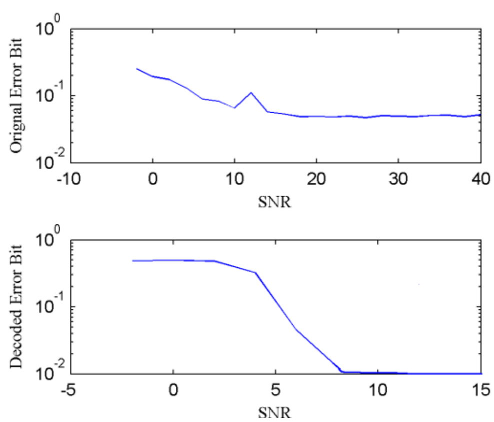

Fig. 16: BER vs SNR (up) raw BER and (down) hard decoded BER with doppler case

BER performance: Figure 15, 16 and 17, respectively show the BER performance (raw and coded) at Gawadar coast for no Doppler case, hard decoding Doppler case and soft decoding Doppler case. From these simulation results we get the evident for the robustness of proposed algorithm specifically for the coded BER of the order of $\mathbf{10^{-4}}$ have been achieved near to **5 dB SNR**. In this algorithm, BER performance can be improved with more receiving element through multi-channel combining.

PERFORMANCE RESULTS FOR THE SIMULATION NEAR PORT OF KARACHI

Doppler scaling factor estimation: Various selected parameters (i.e., Bandwidth, carrier frequency, number

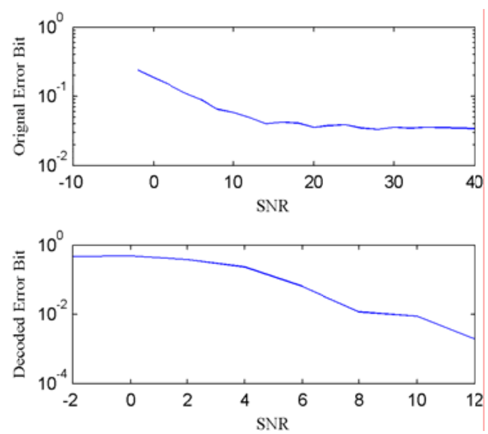

Fig. 17: BER vs SNR (up) raw BER and (down) Soft decoded BER with doppler case

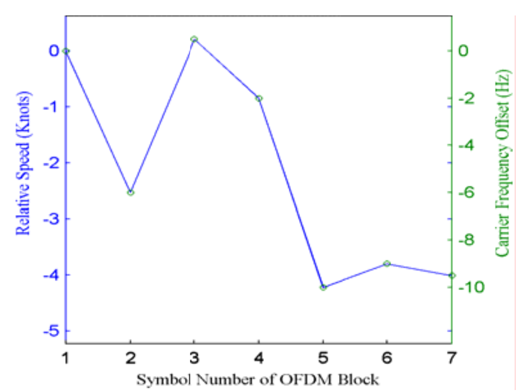

Fig. 18: Tracked CFO and respective relative speeds at 5 dB SNR

subcarriers, guard interval and coding scheme etc.) for this channel are similar to previous case. The distance between transmitter and receiver is $\mathbf{7\ Km}$ and both are placed at the depth of $\mathbf{10\ m.}$ Number of equally spaced Pilot and start-end positioned null bits are also same. CFO tracking per OFDM blocks is shown in the Fig. 18 at $\mathbf{5\ dB\ SNR}$ and Fig. 19 at $\mathbf{25\ dB\ SNR}$. In the both scenarios CFO changes continuously with the relative speed of around $\mathbf{-3}$ to $\mathbf{+3\ Knots}$.

LS channel estimation and symbol detection: Estimated channel through LS method is obtained and the plots of the same on OFDM block 1 and 2 are shown in Fig. 20. In this flat channel, slight delay of $\mathbf{5\ micro\ sec}$ is computed between 2 paths. The concurrent and matched energy peaks revealed that the relative speed difference is not so prominent between block 1 and 7.

Scattering plots of received signal after demodulation can be seen in the Fig. 21 (left to right) for no Doppler case, Hard decoding Doppler compensation case and Soft decoding Doppler compensation case respectively. Without Doppler addition, demodulated signal can be detected accurately without any additional load, however, for other 2 cases, soft decoding is considered bit better for recovery of received bits from the QPSK constellation points.

BER performance: Like previous channel model, the simulation results over this channel also show the satisfactory performance of proposed receiver algorithm. The results are categorically explained in the Fig. 22 to 24. With hard decoding and soft decoding Doppler compensation, the coded BER are low and almost similar with the desired results i.e., the results obtained when Doppler distortion is not considered.

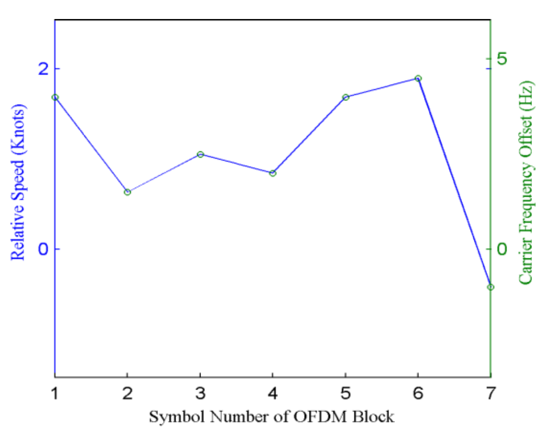

Fig. 19: Tracked CFO and respective relative speeds at 25 dB SNR

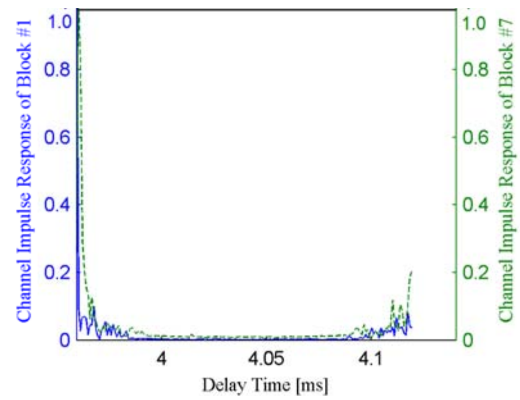

Fig. 20: Channel estimation at OFDM block 1 and 2

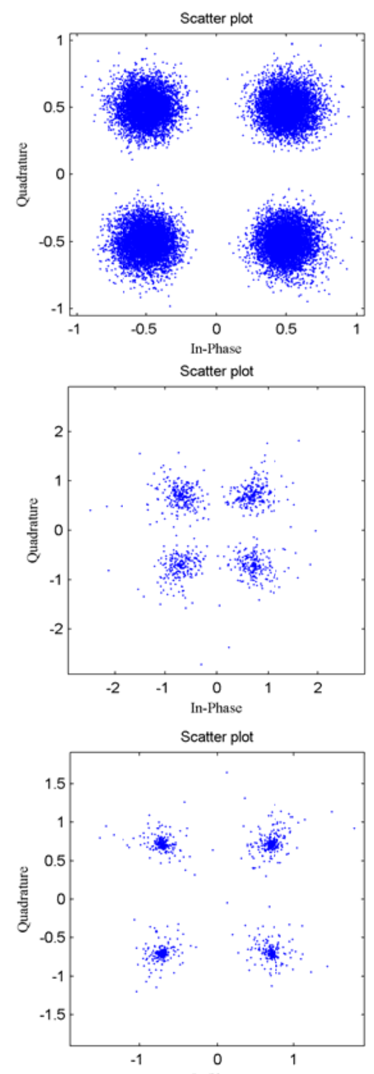

Fig. 21: Scatter plot (up) without doppler (middle) with hard decoding doppler compensation and (below) with soft decoding doppler compensation

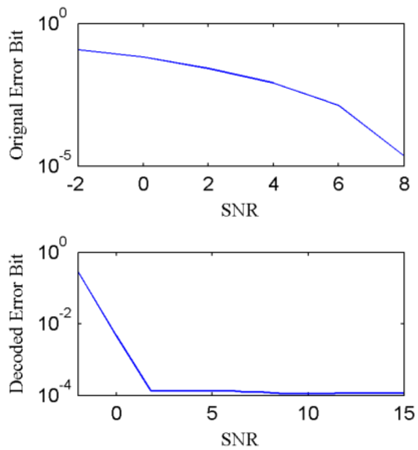

Fig. 22: BER vs SNR (up) raw BER and (down) decoded BER without doppler case

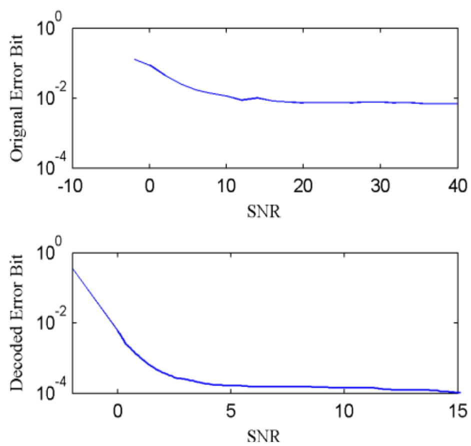

Fig. 23: BER vs SNR (up) raw BER and (down) hard decoded BER with doppler case

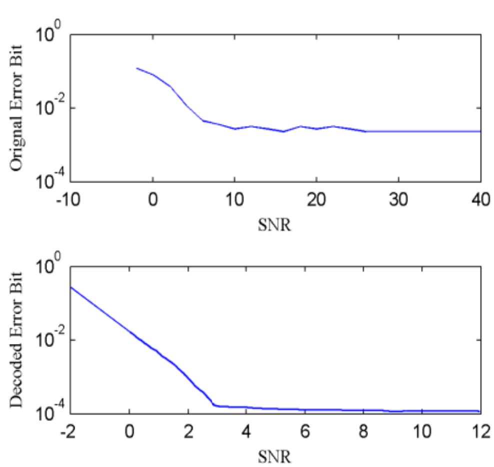

Fig. 24: BER vs SNR (up) raw BER and (down) soft decoded BER with doppler case

CONCLUSION

In this study we have presented the OFDM based simulation work carried out for the two important models of Arabian Sea. Using Bellhop, modeling of selected multipath channel is effectively performed whereas, random Doppler is also modeled in our MATLAB code. Two step approaches on OFDM based communication over the harsh underwater environment like Gawadar and Karachi is analyzed and found feasible for the compensation of dominant Doppler shifts and removal of residual CFO. The receiver algorithm uses pilot used pilot tone for channel estimation and null subcarrier to facilitate the alleviation of Doppler induced receiving bits. Good BER performance using VA and LLR decoding schemes is achieved even with the relative speed of 4.2 Knots between transmitter and receiver. Simulation results suggest that OFDM is a best suitable candidate for high-rate underwater transmission and a basis for the experimental testing/trials.

Other channel model specifically in Arabian Sea will be considered in future research with more improvement in terms of BER. Prior to experimental attempt, nonlinear impulsive noise model will also cater in our channel model for the more realistic results. Moreover, time wrap model for precise Doppler compensation with MMSE and modified MMSE will also the part of research.

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