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Evaluation of WATERMARK Channel for Underwater Communication using Dual Tree Complex Wavelet Transform based Orthogonal Frequency Division Multiplexing Model

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Abstract: Underwater communication is one of the important research areas which involves design and development of communication systems that can demonstrate high data rate and low Bit Error Rate (BER). In this work three different modulation schemes are compared for their performances in terms of BER and Peak to Average Power Ratio (PAPR). The realistic channel model called WATERMARK is used as a benchmark to evaluate channel performances. The mathematical model is developed in MATLAB and channel environments such as Norway Oslo fjord (NOF1), Norway Continental Shelf (NCS1), Brest Commercial Harbour (BCH1), Kauai (KAU1, KAU2) are considered for modelling different underwater channels. The data symbols are modulated using Dual Tree Complex Wavelet Transform (DTCWT) Orthogonal Frequency Division Multiplexing (OFDM) model to generate multi subcarriers and are demodulated at the receiver considering underwater channel environments. The BER results are evaluated for channel depth less than 10m and 10-50m. An improvement of $2x10^{-2}$ in terms of BER is observed when compared with Fast Fourier Transform (FFT) based OFDM model.

Index Terms: Underwater Acoustic Communication, WATERMARK, Complex Wavelet, OFDM, BER, PAPR.

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most popular techniques for wireless communication that provides high data rates and efficient bandwidth utilization. For Underwater Acoustic Communication (UAC) with dynamic changes in water properties establishing reliable communication link is a challenging task considering OFDM schemes. The OFDM model has multiple building blocks and each of these blocks are computationally intensive and need to be designed appropriately meeting the underwater Modem (Modulator Demodulator) requirements of which power is a priority. In this chapter a detailed discussion is presented on UAC network and challenges in design of OFDM model. UAC plays an important role in all marine military and commercial activities. Activities involve monitoring of marine environment, exploring underwater environment, monitoring of sub sea oil, gas and oceanographic data collection. Over 70% of the earth surface is covered with ocean and there is a vast area to be monitored with relevant applications emerging. Coastal surveillance through autonomous vehicle, communication linking submarines to land, water monitoring, data collection and environmental research are few of the applications that are significant topics of research that involves UAC. Similar to the internet of things on land there is going to be lot of emphasis and applications around internet of things on underwater, which is seen as the future for exploring oceans. For UAC it is required to deploy sensor nodes at different locations that communicate with each other through acoustic signals. All these nodes are powered by batteries, and it is required to ensure that the sensor nodes are low power devices and the devices or nodes conserve energy as low as possible but still perform the task of communication. These devices are called as underwater wireless modems that are energy efficient and also are robust in connecting devices through wireless link. Charging mechanism and battery management technology are key challenges in design of modem. The Modems perform communication task using appropriate modulation schemes compactable to underwater applications. Direct Sequence Spread Spectrum (DSSS) is the most popular modulation method for UAC as it is very robust even in varying channel environments. The environmental factors such as wind, temperature, underwater currents and noise impact the channel properties and hence the modulation methods. OFDM and swept frequency or chirp modulation schemes are being tried for underwater successfully. The complexity of generating OFDM data requires large power, and this impacts the battery life. The advantage of OFDM over DSSS is the higher data rate that is very attractive for all UAC networks. UAC is a real challenge for researchers and more realistic underwater channel models is needed for evaluation of OFDM systems. In this work two major issues are addressed, one is the complex wavelet based OFDM model with error coding techniques to improve BER and second is evaluation of the model considering realistic underwater channel models. BER performances are computed considering three different OFDM models (FFT, DWT and DTCWT) with error coding techniques and symbol mapping techniques considering different realistic underwater channel environments. The overview of this paper is as follows, Section 2 presents motivation, Section 3 presents contribution, Section 4 discusses related work, Section 5 presents discussion on underwater channel model, section 6 presents the complex wavelet OFDM model, section 7 discusses the BER performances of OFDM model in realistic underwater channel environment and section 8 is conclusion.

2. Motivation Behind this Work

The OFDM module need to be designed for reconfigurability as the channel characteristics has dynamic behaviour and accordingly the sub carriers need to be selected for modulation. As there are very few literature on hardware implementation of DTCWT structures it is required to develop a benchmark architecture that can be configured as IP for all applications. In addition to selection, design and optimization of DTCWT structure for OFDM it is also required to identify suitable error coding technique that together with DTCTW achieve better BER and reduced PAPR. The underwater channel conditions are very complex and suitable combination of error coding methods and sub carrier modulation schemes need to be designed.

The major challenges in the design of underwater communication channel are as follows:

- Highly time-variant underwater acoustic channel characteristics, multipath propagation, Doppler effect, acoustic absorption, variable propagation delays, fading problems. and sometimes low signal-to-noise ratio (SNR)
- Bandwidth is severely limited in order of KHz because underwater acoustic propagation is efficient for low frequency signals
- High bit error rates
- Underwater modems are susceptible to failures because of fouling, corrosion, etc.

The primary aim of this work is "Evaluation of sub-carrier modulation techniques for underwater applications".
The aim of this work is attained by working on the objectives defined as follows:

- Evaluation of BER performances of FFT/DWT/DTCWT based OFDM model for underwater channel.
- Design and implementation of DTCWT-OFDM architecture for underwater channel.

3. Contribution of Paper

Most of the studies in literature on underwater channel is based on mathematical model and the properties of communication system is evaluated based on simulation models. It is observed through literature that the time varying underwater channel severely impacts the OFDM signal characteristics. With convolution coding and FFT based modulation considered, the OFDM signal is completely distorted and decoding of message is highly affected. In order to improvise the BER performances, shift invariant modulation schemes combined with suitable channel model is proposed.

- Very recently the WATERMARK channel is reported in literature and is develop as a tool for underwater community. underWater AcousTic channEl Replay benchMARK (WATERMARK) channel is a realistic tool that is considered for validation of modulation techniques in underwater channel.
- WATERMARK is programmed in MATLAB and is freely available for benchmarking underwater system. The

frequency bands are from 4-8 kHz, 10-18 kHz and 32.5–37.5 kHz with both single hydrophone and array receivers considered in the experimental setup to develop the empirical underwater channel model.

- Five channels Norway Oslofjord (NOF1), Norway Continental Shelf (NCS1), Kauai (KAU1, KAU2) and Brest Commercial Harbour (BCH1) parameters are captured by mounting the hydrophones at the bottom of the ocean, towed by ship and placed at the bottom of the ocean respectively. The hydrophone records the sound characteristics in the five different channel environments for 30-60 s.
- In this work three different OFDM models are developed using FFT/DWT/DTCWT that performs modulation using 16 sub-carriers and are evaluated for their performances considering WATERMARK channel environment.
- The channel depth of 10 m and 10-50 m is considered as one of the channel properties and BER is captured for Eb/No varying from -10 to +10 db.
- BER results were presented and DTCWT is shift invariant and it is expected that there will be no large variation with Doppler shifts or channel depth. In all three channel conditions (NOF1/NCS1/BCH1), DTCWT-OFDM model is exhibiting lower BER compared with all other (FFT/DWT) model. It is also observed that BER results of DTCWT-OFDM model also remains within limits for changes in Eb/No.

4. Related Works

OFDM found to be advantageous for underwater communication system due to its frequency selective process and providing flat fading, narrow band sub channel carrier modulation methods[1,2]. Narrow band interference elimination in OFDM to combat channel interference and symbol interference that are caused due to multipaths are reduced with use of wavelet based OFDM methods [3,4]. Wavelet filters provide the advantage due to its time limited basis function, non-rectangular window functions and denoising methods [5,6]. Wavelet transform based OFDM is advantageous as the filter bank structure is flexible in sub carrier modulation and demodulation [7]. Cyclic prefix is not required in wavelet based OFDM and this provide nearly 20% advantage in bandwidth efficiency. Another 8% of space saving in terms of bandwidth is achieved due to avoidance of pilot carrier [8]. Shift invariance property impacts energy distribution in wavelet subbands if the input signal is time shifted. In underwater communication the input signal is non-stationary due to Doppler shifts and dispersion which severely affects energy distribution in wavelet domain. To overcome the limitations of shift variance DTCWT which is shift invariance is used for OFDM sub carrier modulation [9-10]. The performances of DTCWT based OFDM model considering 16-QAM and 64-QAM symbol mapping schemes and with sub carriers varying from 64 to 1024 is analyzed [11]. Studies on different DTCWT filters (such as 5/3, 9/7 13/9, 10/10 and 6/6) have also been reported to analyze the OFDM performances in terms of BER, PAPR and Power Spectral Density (PSD). DTCWT based OFDM is observed to outperform wavelet based OFDM in terms of BER change from 10^{-3} to 10^{-6} with 64-QAM. It is also identified that antonini 9/7 filter and 10/10 tap filters are most suited for OFDM achieving lower BER compared all other DTCWT filters [12] also the improvement of 3dB over FFT based OFDM and wavelet based OFDM is also demonstrated. Underwater channel is said to be a poor communication channel with high propagation delay and this affects BER significantly. Chanel coding is used to compensate to decrease BER at the cost of bandwidth due to redundancy introduced in the data. Low Density Parity Check (LDPC), Convolutional Coding (CC), Reed Solomon (RS) coding and Turbo Codding is the most preferred error coding for underwater channels. BER is reduced from 10^{-2} to 10^{-4} by use of CC and RS coding [13].

In order to evaluate the performances of complex wavelet based OFDM system it is required to consider the underwater channel model such as normal wave model, radiation model, sound field model and parabolic model [14]. There are two acoustic channel models one is the deep vertical channel model and other the shallow water multi path model. Most of the studies in literature on these channels is based on mathematical models and the properties of communication system is evaluated based on simulation mod-els. Bathymetry data studies carried out in the Indian Ocean, Arabian Sea and Bay of Bengal is found that the sound velocity ranges between 1490 m/s to 1540 m/s. Mackenzie propagation model for computing speed of sound considering variation in temperature and density are obtained from Bay of Bengal with real time data [15]. AUVNet Sim [16], Xie and Gibson model [17], Harris model [18], URICK and THROP model [19] and Bellhop model are few of the underwater channel models that have been reported in literature for evaluation of underwater communication system. However, the dynamic nature of underwater medium which involves movement of living animals, climate changes, tides, movement of ships and human activity impacts channel properties. There is a need for considering more realistic underwater channel models for evaluation of OFDM systems.
From the literature studies carried out the following are the major observations:

- For underwater network the Modems need to be robust, reliable and also be power efficient.
- PAPR is a critical parameter to achieve high data rate and low power requirements in design of underwater Modems.
- DTCWT based OFDM schemes have been demonstrated to be superior than that of conventional OFDM models in terms of BER and PAPR, however there is observed degradation in BER performances with use of different DTCWT filters.
- The existing models for UAC based on OFDM support 1024 sub carriers and for high data rate it is required to

have 2048, 4096 sub carrier schemes with reconfigurability options on the hardware platform.

- In order to address dynamic nature of UAC channel it is required to use flexible and adaptive error coding techniques. Viterbi and turbo coding methods are widely used, however for meeting the dynamic underwater channel requirements there is a need for development of dynamic error coding schemes.
- To meet the requirements of underwater channel environment shift invariant and dynamically reconfigurable modulation scheme and error coding scheme respectively is required to be designed.

5. Underwater Channel Benchmarking

Underwater channel are complex in nature and any modulation scheme developed need to be evaluated considering the actual parameters for underwater channel models. There are different channel models and simulators [20, 21] that provide realism and completeness for evaluation of modulation systems. The underwater Acoustic Channel Replay benchmark is a simulator developed [22] and is made available in MATLAB environment. Underwater simulation tool underWater acousTic channEl Replay benchmark (WATERMARK) is realistic tool validated with FFI channel simulator "Mime" and is recommended for evaluation of underwater communication system [23]. Scripps Institution of Oceanography approved the model considering array data provided by experiments carried out by Kauai Acomms MURI 2011 [24]. According to the model developed the principle of operation of the channel is based on the expression as in Eq. (1).

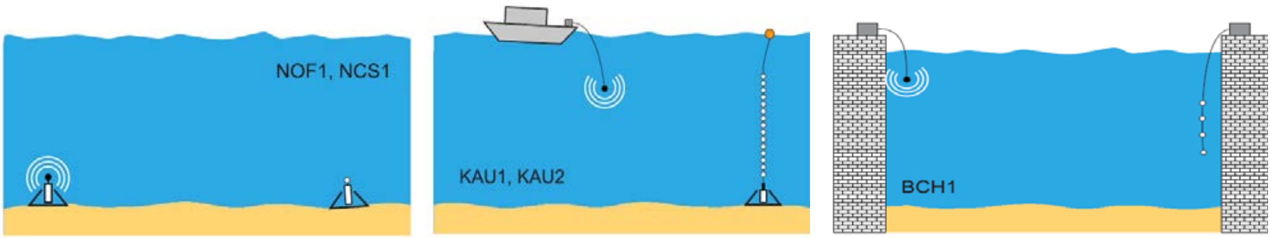
$$y(t) = \int_{-\infty}^{\infty} \hat{h}(t,\tau)x(t-\tau)d + n(t) \quad (1)$$

The input signal x(t) is convolved with h(t,τ) which is a time varying channel response and n(t) is the noise. The output is the distorted signal y(t). According to the channel model the noise in the channel is considered based on correlative channel sounders and the combination of Mime discussed in [25-26]. Time Varying Impulse Response (TVIR) measurements for Watermark for five channels are summarized in Table 1. The five channels NOF1, NCS1, KAU1, KAU2 and BCH1 parameters are captured by mounting the hydrophones at the bottom of the ocean, towed by ship and placed at the bottom of the ocean respectively. The hydrophone records the sound characteristics in the five different channel environments for 30-60s.

Table 1. Watermark channel parameters

Name	NOF1	NCS1	BCH1	KAU1	KAU2
Environment	Fjord	Shelf	Harbor	Shelf	Shelf
Time of year	June	June	May	July	July
Range	750 m	540 m	800 m	1080 m	3160 m
Water depth	10 m	80 m	20 m	100 m	100 m
Transmitter depl.	Bottom	Bottom	Suspended	Towed	Towed
Receiver depl.	Bottom	Bottom	Suspended	Suspended	Suspended
Probe signal type	LFM train	Pseudonoise	Pseudonoise	LFM train	LFM train
-3dB frequency band	10-18 kHz	10-18 kHz	32.5-37.5 kHz	4-8 kHz	4-8 kHz
Roll-off fact.	1/8	1/8	1/10	1/8	1/8
Sounding duration	32.9 s	32.6 s	59.4 s	32.9 s	32.9 s
Delay coverage	128 ms	32 ms	102 ms	128 ms	128 ms
Doppler coverage	7.8 Hz	31.4 Hz	9.8 Hz	7.8 Hz	7.8 Hz
Type	SISO	SISO	SIMO	SIMO	SIMO
#hydrophones	1	1	4	16	16
Element spacing	-	-	1 m	3.75 m	3.75 m
# cycles	60	60	1	1	1
Cycle time	400 s	600 s	-	-	-
Total play time	33 min	33 min	1 min	33 s	33 s

Fig. 1 presents the experimental setup for measuring the underwater channel considering five different environments. The NOF1 channel characteristics are shown in Fig. 2, before the first arrival the delay is arbitrarily placed in the channel characterization. The late arrivals are Doppler distorted due to surface sea interactions and has no frequency spread. There is also a streak of delayed clutter at $\upsilon = 0$, due to stationary scatterers. Despite the scattering, most energy is concentrated in a narrow delay-Doppler window (between $\tau = 3$ ms and $\tau = 5$ ms, at $\upsilon = 0$ Hz). From the underwater channels characteristics it is easy to evaluate the channel models correlating with the channel characteristics. Differences and commonality of channel variations are observed and use of statistical methods are developed easily for benchmarking. The WATERMARK channel is developed considering the receiver that are arranged in array are time synchronized hence the results that captured using the receiver array provide accurate information on channel characteristics. The input signals with frequency bands of 10-18 kHz, 4-8 kHz and 32.5 to 37.5 KHz considered for evaluating BER performances. The input signal considered is passband signal that comprises of communication packets. The test input data need to be defined indicating the number of bits per packet as defined by the physical layer information. The WATERMARK functions such as SIMO and SISO are used to retrieve the packets from the channel using functions “replayfilter”[27-29]. Two types of modulation schemes are defined as test cases for evaluation of WATERMARK channel considering all the test environments. The QPSK and DSSS schemes are recommended for evaluation. NOF1 is a relatively benign communication channel. It is required to evaluate the WATERMARK channel with OFDM model considering the conventional OFDM or the FFT-OFDM, DWT-OFDM and DTCWT-OFDM. In this work, a detailed study of all above modulation schemes considering with and without WATERMARK channel is carried out.



(a) NOF1 and NCS1 channel model (b) KAU1 and KAU2 channel model (c) BCH1 channel model

Fig.1. Experimental setup for measuring underwater channel properties

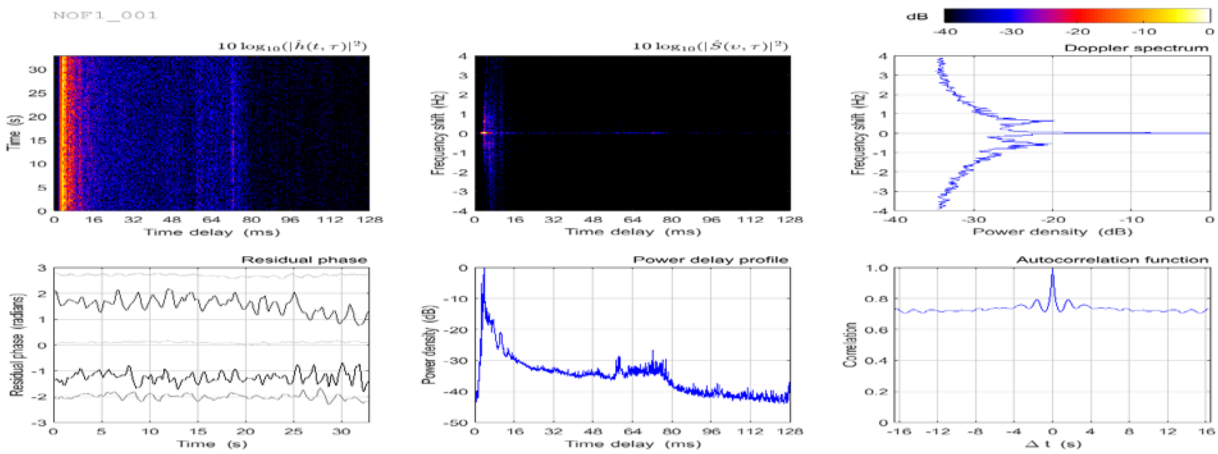


Fig.2. Channel characteristics of NOF1

6. DTCWT Model for OFDM

In OFDM based modulation the symbols generated from the symbol modulator modules are converted from serial to parallel vectors [30]. The Inverse DTCWT module that comprises of multi-stage synthesis filter banks processes the parallel data vector and combines into a single component of data that is serially read out. Fig. 3 presents the OFDM modulator-demodulator block diagram. The digital up converter/ down converter module is designed to choose the carrier frequency for the modulated signal for transmission over the acoustic channel. In order to address the noise variations in the channel the error coding module encodes the input data with redundant data bits. In this work, convolutional encoder is used for error coding. The signal received at the demodulator is processed by the digital down converter/ up converter and the processed data is demodulated by the DTCWT module that generates parallel data vectors. The Parallel-Serial (P-S) converter serializes the data symbols for demodulation and error decoding. The primary building block in the OFDM system is the design and implementation of DTCWT-Inverse DTCWT module. The advantage of using wavelet based sub carrier modulation over FFT based modulation is the reconfiguration of modulator-demodulator with regard to number of sub carriers. In the case of wavelet based modulation-demodulation the number of stages or levels of filter bank structure can be set to decide the sub carrier selection process. Fig. 4 presents the inverse DTCWT structure with 7 levels of synthesis filter banks that can process 16 input vectors to generate the OFDM data at the output represented as X'_R and X'_I. The output X'_R and X'_I are combined together by the adder module to generate stream of OFDM data.

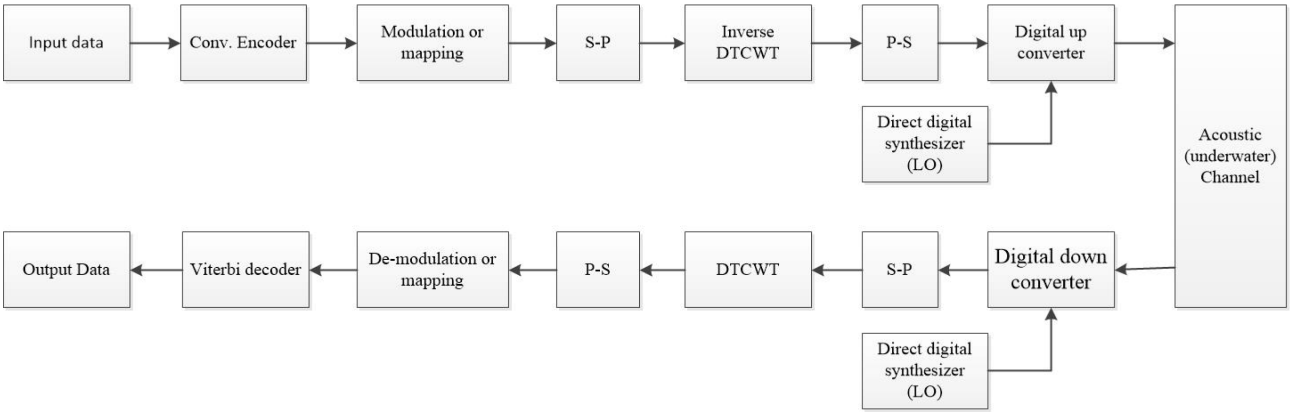


Fig.3. OFDM modulator and demodulator

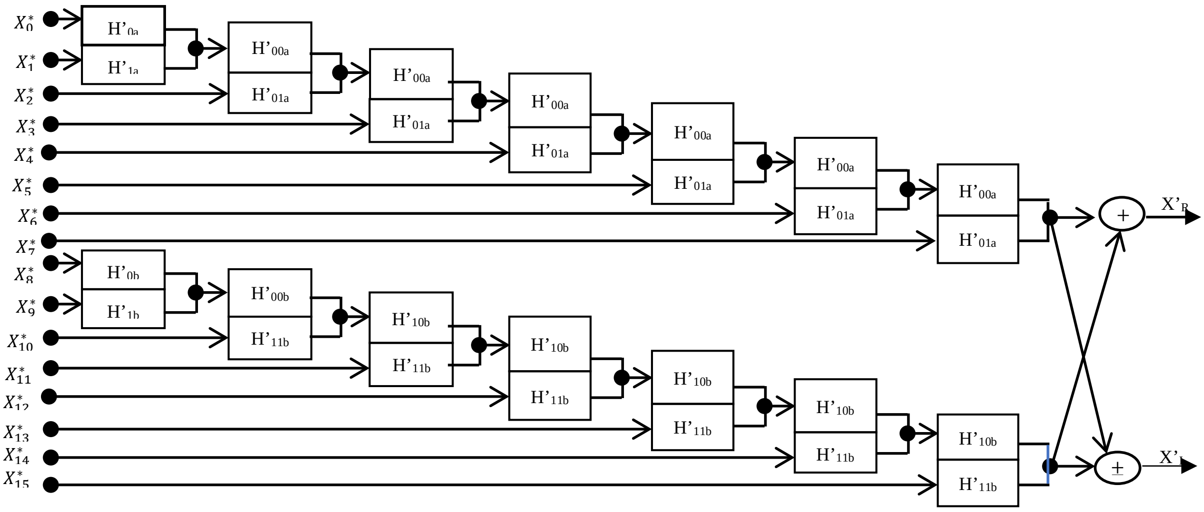


Fig.4. Seven stage inverse DTCWT – for OFDM modulation

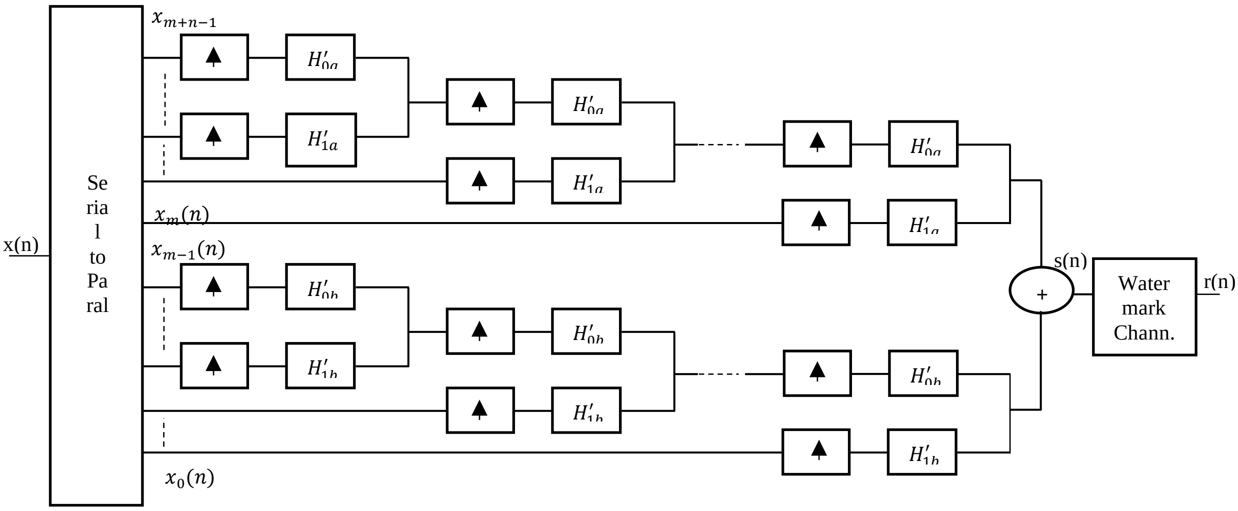


Fig.5. DTCWT based OFDM modulation with WATERMARK channel

Fig. 5 provides the proposed block diagram of OFDM modulation using DTCWT. The input data stream x(n) (generated from QAM) is converted to N parallel data streams. The data stream $x_o(n)$, $x_1(n)$….., $x_{m-1}(n)$ is processed by the real-DTCWT filter coefficients and data stream $x_m(n)$, $x_{m+1}(n)$….., $x_{m+n-1}(n)$ is processed by the imaginary-DTCWT filters coefficients. The parallel data stream is processed by the filter bank of complex wavelet reconstruction structure. Each of the filters comprises of up sampling (↑) and filtering operation (H'_{XX}). The outputs of all filters are combined together and is denoted as s(n). The combined signal representing OFDM is sent to WATERMARK channel. The channel output denotes r(n) is processed by the filter bank of complex wavelet decomposition structure. Each of the filters comprising of filters (H_{xx}) and down sampling (↓) operations (not shown in Fig.). The output of decomposition filter bank is converted to serial stream of data by the parallel to serial converter.

The time varying WATERMARK channel with multipath channel impulse response is represented as in Eq. (2)

$$h(\tau,t) = \sum_{i=1}^{S} \xi_i(t)\delta\big(\tau - \tau_i(t)\big) \quad (2)$$

The parameters S represent total number of paths, ξ_i and τ_i represents path attenuation and path delay of the ith time varying path respectively. All the paths are with Doppler scaling factor $\alpha(t)$ and is given as in Eq. (3)

$$\tau_i(t) \approx \tau_i - \alpha(t)t \quad (3)$$

The receiver output r(n) is represented mathematically as in Eq. (4)

$$r(n) = s(n) * h(n) + \eta(n) \quad (4)$$

s(n) represents modulated data and h(n) is the WATERMARK channel impulse response. Additional noise in the channel is represented as $\eta(n)$**.** Considering the channel as WATERMARK it is required to evaluate OFDM models with different modulation schemes and demonstrate advantages of shift invariant schemes for OFDM system. Table 2 summarizes the specifications for OFDM model developed in this work.

Table 2. OFDM parameters

Frequency Band	Carrier frequency spacing (Hz)	IDTCWT architecture	No. of DTCWT stages	Transmission Frequency
9-15 kHz	46, 23.2, 11.5 and 5.75	128, 256, 512 and 1024	7, 8, 9 and 10	40 kHz –B1
20-26 kHz	46, 23.2, 11.5 and 5.75	128, 256, 512 and 1024	7, 8, 9 and 10	48 kHz – B2
32-38 kHz	46, 23.2, 11.5 and 5.75	128, 256, 512 and 1024	7, 8, 9 and 10	54 kHz – B3

In first case, the QPSK modulated data is rearranged to parallel data using the serial to parallel converter of size 128. The IDTCWT model of 7 stages are designed using low pass and high pass synthesis filters based on 10-tap complex wavelet filters. At every stage the low pass and high pass filter outputs are up sampled by padding zeros and the filtered output are averaged to generate the modulated data. The OFDM modulated data is up converted to any of the three bands (B1, B2, B3) frequency band using the up converter. The OFDM signal is a complex data and hence the real and imaginary OFDM symbols are separated and up converted using orthogonally shifted carriers. The up converted data is converted to analog domain using 10-bit ADC with maximum intensity set to 512 units. The OFDM signal which is analog data is transmitted over underwater channel with multipath and Doppler shifts. At the receiver the OFDM signal from the channel is demodulated to recover the QPSK symbols using DTCWT processing and demodulation is carried out to obtain the binary data. BER is computed under various channel conditions and OFDM performances are evaluated.

OFDM Modelling

In order to develop the simulation model of OFDM it is required to study the mathematical model to get a through insight on the parameters that control the performances of OFDM model in different channel environments. In this section a detailed discussion on mathematical model is presented.

OFDM Signals $O_m\,(t)$ with M sub-carriers is represented mathematically as in Eq. (5)

$$O_m\,(t) = \sum_n d_m(n)\, e^{jm\Delta w(t-nT')} g(t-nT') \quad (5)$$

where $d_m(n)$ is input data, g(t) is rectangular pulse and m = 0, 1, ... M-1 represents number of channels. OFDM signal in Eq. (5) is time shifted in frequency and is represented in Eq. (6).

$$S(t) = Re\{\sum_{m=0}^{M-1} O_m(t)e^{j2\pi f_0 t}\} \quad (6)$$

The terms, f_0 represents lowest carrier frequency and $f_k = f_0 + k\Delta f$ denotes kth carrier frequency and $S(t)$ is time shifted signal. The symbol rate is assumed to be R and is computed as $\frac{M}{T+T_g}$ symbols per second and signal bandwidth is defined as B given by MΔf. Bandwidth efficiency is computed as $\frac{R}{B} = \frac{1}{(1+T_g/T)}$ sps/Hz. The channel impulse response $C(t,n)$ considering nth OFDM block interval $t \in (nT',\ nT'+T')$ is given as in Eq. (7), where, $A_p(n\ )$ unknown complex-valued channel coefficient and J_p is the corresponding delay.

$$C(t,n) = \sum_p A_p(n)\ \delta\ \big(t + a(n)t - J_p(n)\big) \quad (7)$$

The channel transfer function $C(f,n)$ for nth block interval is given in Eq. (8).

$$C(f,n) = \sum_p A_p(n)\ e^{-j2\pi f J_p(n)/(1+\alpha(n))} \tag{8}$$

The modulated signal $Y_k(n)$ transmitted over communication channel will be distorted with channel noise (Additive Noise $W_k(n)$) and is expressed as in Eq. (9).

$$Y_k(n) = \sum_{l=0}^{M-1} Y_{k,l}(n) + W_k(n) \tag{9}$$

The signal $Y_{k,l}(n)$ in the frequency domain is represented as in Eq. (10), where θ_l represents the phase information of the carrier signal.

$$Y_{k,l}(n) = C_k(n)\, S_{k,l}\, d_l(n)\, e^{j\theta_l(n)} \tag{10}$$

Based on the above equations, empirical models for UAC channel is written as in Eq. (11).

$$A(d, f_k) = d^e\, a(f_k)^d \tag{11}$$

where, A is signal attenuation constant, d is the distance at which transmitter is positioned, f_k is the selected subcarrier frequency and e is the assumed path loss exponent of 1.5. The term a (f_k) is computed considering Thorp's formula in dB/Km and is expressed as in Eq. (12).

$$10\log\ a(f_k) = \frac{0.11 f_k^2}{1+f_k^2} + \frac{44 f_k^2}{4100+f_k^2} + 2.75 * 10^{-4} f_k^2 + 0.003 \tag{12}$$

The noise variance is modelled as in Eq. (13),

$$10\log N(f_k) = N_1 - \eta\log(f_k) + 10\log\Delta(f_k) \tag{13}$$

N_1 & η are constants, assumed to be 50dB µP_a per Hz and 18dB/decade respectively. From the empirical models which is an approximate estimate of underwater channel simulation model is developed. With the simulation model of underwater channel different modulation schemes are developed and evaluated for its performances. In the next section, detailed discussion on wavelet based OFDM model is presented and its performance considering underwater channel model is evaluated.

7. Evaluation of OFDM with WATERMARK Channel

In order to evaluate the impact of WATERMARK(WM) on OFDM performance a test setup is carried out in software environment to study characteristics of OFDM system. Fig. 6 presents the test setup developed in MATLAB environment for study of OFDM model and its performances in the presence of underwater channel. The input data of 9600 bits is generated using random number generator function and is grouped into 100 packets each of 96 bits. The 100 frames are encoded and transmitted in packets using OFDM method. Each of the frames is convolutional encoded using (171, 133)-Galois function and the error coded data is interleaved to increase data rate [31-32]. The interleaved data is modulated using QAM. The modulated QAM symbols are inserted with pilot carrier for data synchronization. IFFT is carried out to generated OFDM signal considering 64 sub carriers and cyclic prefix is carried out considering 20% of the total sub carriers. The OFDM signal is convolved with the WATERMARK channel and the signal is decoded at the receiver section. The decoded message is compared with the input message to compute BER. In order to evaluate the impact of underwater channel on the OFDM performances, BER is also computed considering AWGN channel. Fig. 7 presents the NOF1 channel time domain response for a generic input data.

Fig. 8 presents the BER performances of OFDM model. The BER of OFDM model with AWGN exhibits conventional response in the SNR range of 0 dB to 16 dB with variations of 10^{-4} BER. The BER performances of OFDM model in WATERMARK channel environment is completely distorted and the BER varies between 0.505 to 0.407 in the SNR variations of 0 dB to 15 dB. From the comparison it is observed that the time varying underwater channel severely impacts the OFDM signal characteristics. With convolution coding and FFT based modulation considered in this study the OFDM signal is completely distorted and decoding of message is highly affected. In order to improvise the BER performances, shift invariant modulation schemes combined with error coding schemes are proposed. The OFDM model with 1024 samples, centre frequency set to 14 kHz, three multipath with delay of 0, 1.5×10^{-4}, 2.5×10^{-4}, Doppler frequency varying from 1 to 100 Hz and transmitter power of 10 W is set as simulation parameters. BER results for three different channels are estimated considering all three modulation schemes (FFT, DWT, and DTCWT). BER results are compared with different channel depths and are discussed in detail.

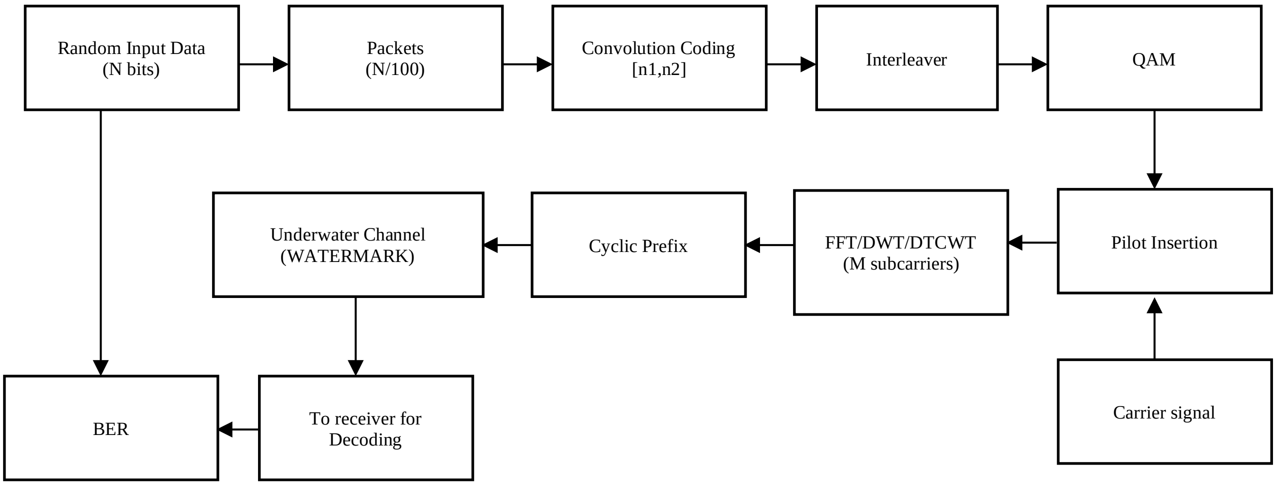


Fig.6. Test setup for WATERMARK channel evaluation

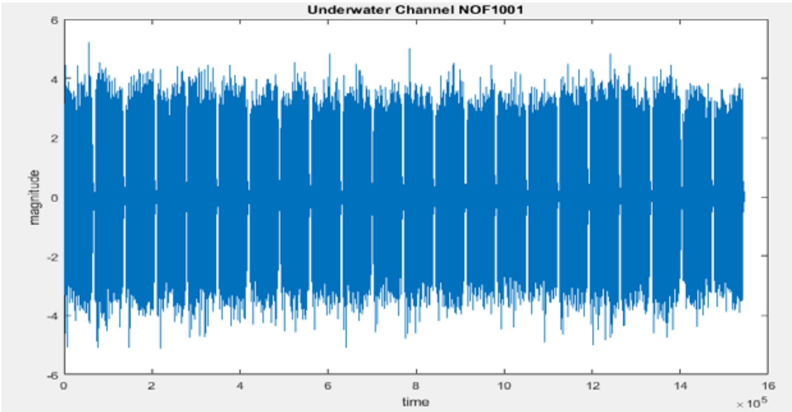
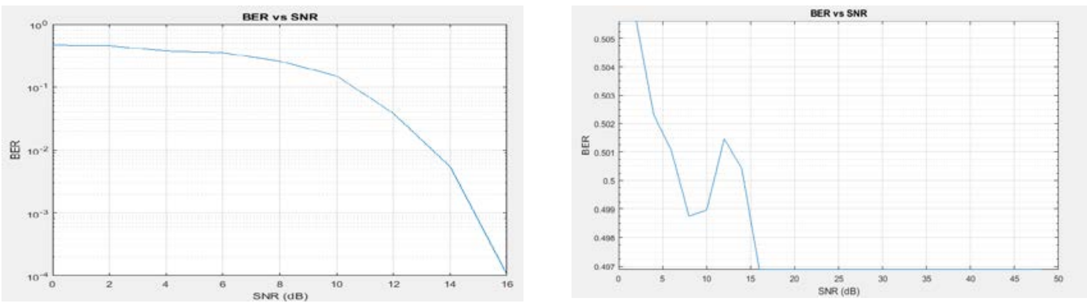
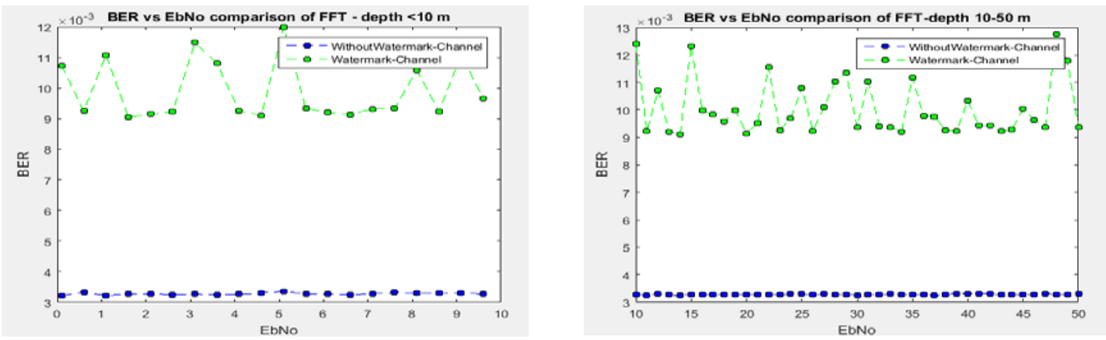


Fig.7. NOF1 channel time domain response



(a) In AWGN channel environment (b) In WATERMARK channel environment

Fig.8. BER performances of OFDM model

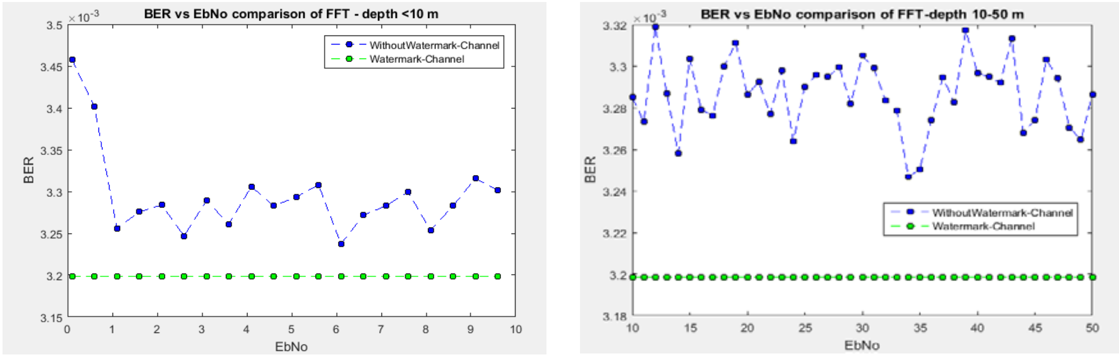


(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.9. BER comparison FFT-OFDM NOF1 channel

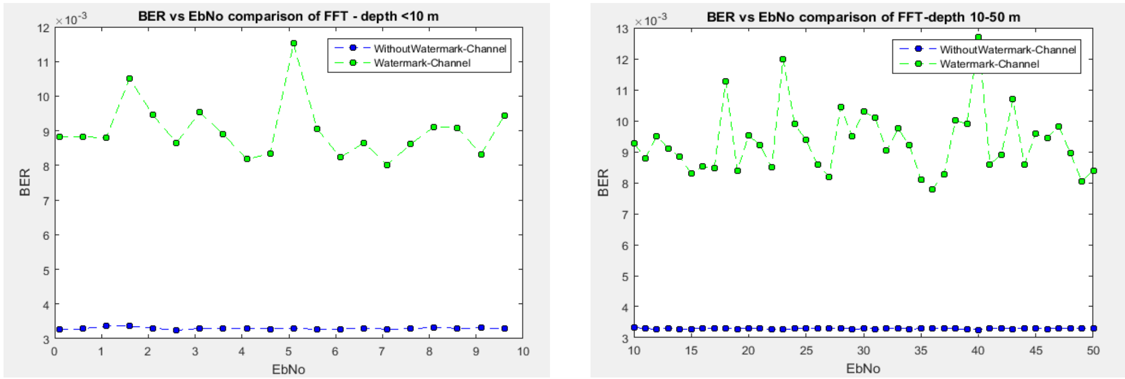
BER Comparison and discussion of Considering Watermark Channels

Fig. 9 to Fig. 15 presents BER simulation results for different channels (NOF1, NCS1, and BCH1). The channel depths are varied of less than 10 m and 10- 50 m is set for OFDM operation by changing the Doppler frequency shifts. BER results obtained for Eb/No varying from 0 dB to 10 dB. BER results for channel conditions with and without WATERMARK are generated from the simulations considering all three modulation schemes.



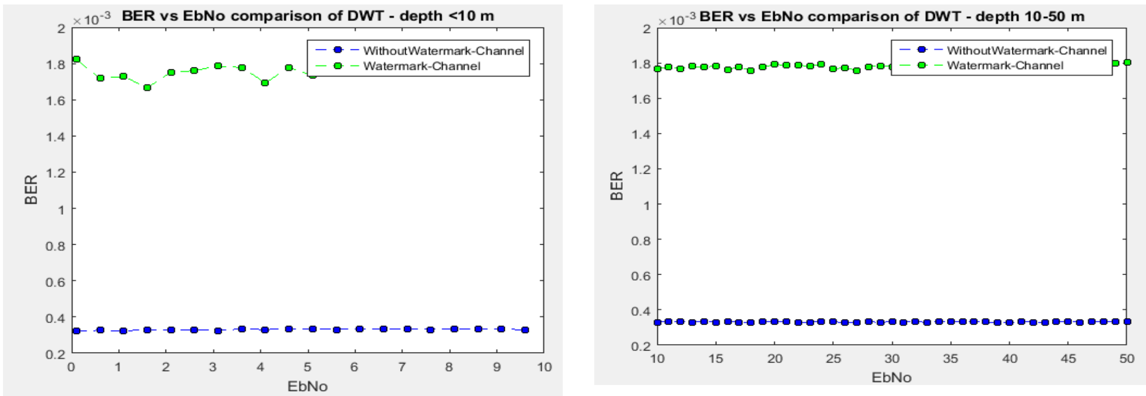
(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.10. BER comparison FFT-OFDM NCS1 channel



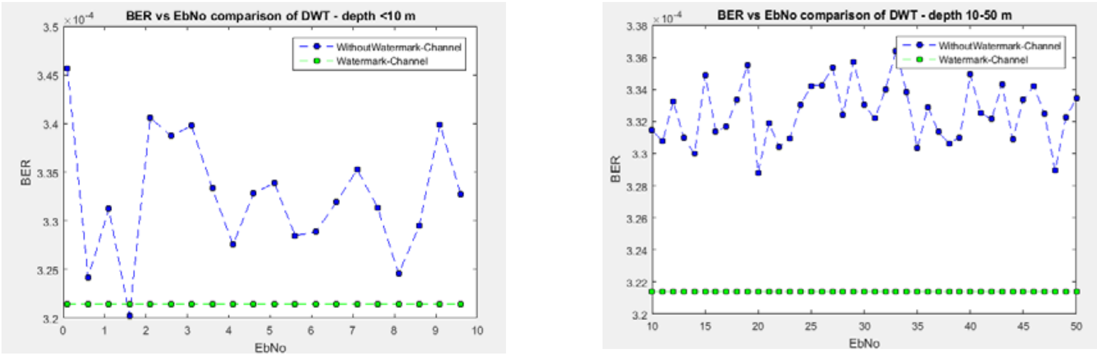
(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.11. BER comparison FFT-OFDM BCH1 channel



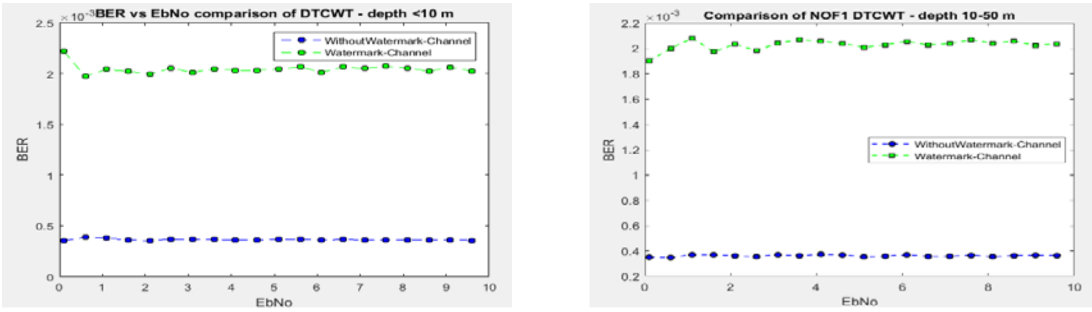
(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.12. BER comparison DWT-OFDM NOF1 channel



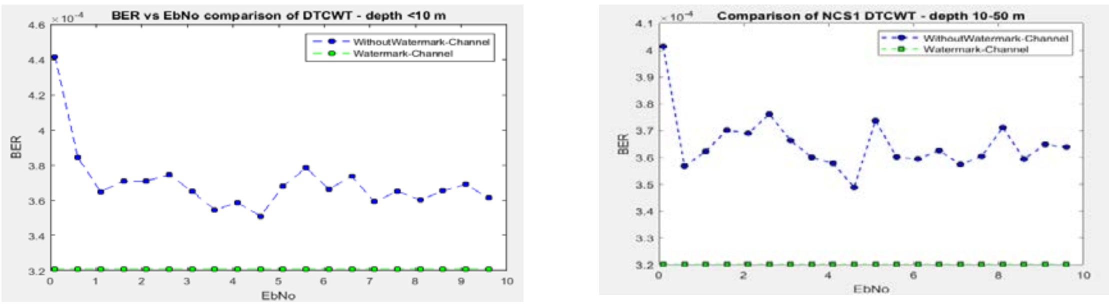
(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.13. BER comparison DWT-OFDM NCS1 channel



(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.14. BER comparison DTCWT-OFDM NOF1 channel



(a) Less than 10 m depth (b) 10 – 50 m depth

Fig.15. BER comparison DTCWT-OFDM NCS1 channel

Table 3 to Table 5 summarizes the BER performances of all three modulation schemes. DTCWT-OFDM model performance is compared with DWT and FFT based model. DTCWT is shift invariant and it is expected that there will be no large variation in BER performances with Doppler shifts or channel depth. In all three channel conditions, DTCWT based model is exhibiting lower BER compared with all other model. It is also identified that the DTCWT-OFDM model BER results do not change by a larger value considering with and without WATERMARK channel and remains within limits for changes in Eb/No.

Table 3. BER comparison considering NOF1 channel

Technique	**E_b/N_o**	**<10m Depth**		**10-50m Depth**	
		With WM	**Without WM**	**With WM**	**Without WM**
DWT	0.1	2.30×10^{-3}	0.043×10^{-3}	1.93×10^{-3}	0.039×10^{-3}
	9.6	2.05×10^{-3}	0.036×10^{-3}	2.24×10^{-3}	0.036×10^{-3}
DTCWT	0.1	1.87×10^{-3}	0.03×10^{-3}	1.65×10^{-3}	0.03×10^{-3}
	9.6	1.75×10^{-3}	0.03×10^{-3}	2.2×10^{-3}	0.03×10^{-3}
FFT	0.1	8.35×10^{-3}	3.28×10^{-3}	9.49×10^{-3}	3.33×10^{-3}
	9.6	9.47×10^{-3}	3.26×10^{-3}	9.32×10^{-3}	3.28×10^{-3}

Table 4. BER comparison considering NCS1 channel

Technique	E_b/N_o	<10m Depth		10-50m Depth	
		With WM	Without WM	With WM	Without WM
DWT	0.1	$3.2x10^{-4}$	$3.6x10^{-4}$	$3.19x10^{-4}$	$3.04x10^{-4}$
	9.6	$3.18x10^{-4}$	$3.7x10^{-4}$	$3.18x10^{-4}$	$3.06x10^{-4}$
DTCWT	0.1	$3.1x10^{-4}$	$3.18x10^{-4}$	$3.02x10^{-4}$	$3.01x10^{-4}$
	9.6	$3.18x10^{-4}$	$3.30x10^{-4}$	$3.02x10^{-4}$	$3.01x10^{-4}$
FFT	0.1	$3.18x10^{-3}$	$3.01x10^{-3}$	$3.18x10^{-3}$	$3.15x10^{-3}$
	9.6	$3.18x10^{-3}$	$3.08x10^{-3}$	$3.18x10^{-3}$	$3.17x10^{-3}$

Table 5. BER comparison considering BCH1 channel

Technique	E_b/N_o	<10m Depth		10-50m Depth	
		With WM	Without WM	With WM	Without WM
DWT	0.1	$4.0x10^{-4}$	$3.8x10^{-4}$	$3.31x10^{-4}$	$3.04x10^{-4}$
	9.6	$3.67x10^{-4}$	$3.62x10^{-4}$	$3.41x10^{-4}$	$3.02x10^{-4}$
DTCWT	0.1	$3.20x10^{-4}$	$3.18x10^{-4}$	$3.22x10^{-4}$	$3.17x10^{-4}$
	9.6	$3.20x10^{-4}$	$3.30x10^{-4}$	$3.38x10^{-4}$	$3.32x10^{-4}$
FFT	0.1	$8.35x10^{-3}$	$3.28x10^{-3}$	$9.49x10^{-3}$	$3.33x10^{-3}$
	9.6	$9.47x10^{-3}$	$3.26x10^{-3}$	$9.32x10^{-3}$	$3.28x10^{-3}$

Comparing the BER results presented for different channel environments DTCWT-OFDM model is advantageous as it exhibits lower BER, consistent BER from 0 dB to 10 dB and minimum variation in BER in both channel environments. Fig. 16 presents the comparison BER performance of all three models in WATERMARK channel environment considering variation in SNR from 0 to 40 dB. From the simulation results it is demonstrated that the proposed DTCWT-OFDM model is superior to all other models in terms of BER. Table 6 compares the BER performances of all three schemes considering three different SNRs. From the comparison of BER performances, DTCWT is found to be superior to the two other methods.

Table 6. Comparison of BER

Schemes	5 dB SNR	10 dB SNR	20 dB SNR
FFT-OFDM	4×10^{-2}	3×10^{-2}	2.5×10^{-2}
DWT-OFDM	3.5×10^{-2}	2.5×10^{-2}	5×10^{-3}
DTCWT-OFDM	3×10^{-2}	2×10^{-2}	1.2×10^{-3}

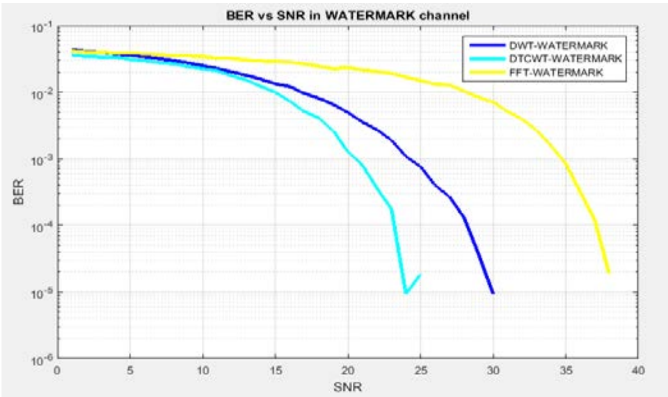


Fig.16. BER and PAPR performances of all three models WATREMARK channel

8. Conclusions

With increase in demand for development of low power and high data rate MODEMS in underwater applications there is a need for OFDM modulation schemes that addresses the dynamic challenges in underwater channel. DTCWT-OFDM model are gaining preferences over existing OFDM model due to robust operations in shift varying environments. WATERMARK channel is a realistic tool that is considered for validation of modulation techniques in underwater channel. WATERMARK proposes five scenarios (NOF1, NCS1, BCH, KAU1 and KAU2) of channel models that depict the underwater channel characteristic. Any modulation schemes developed for underwater applications are considering WATERMARK model for evaluation of such schemes. In this work, the OFDM model is developed using DTCWT that performs modulation using 16 sub-carriers is evaluated for its performance using WATERMARK channel. Input data is encoded for error correction capability and modulated data is transmitted through WATERMARK channel. The received data is decoded to capture BER. The channel depth of 10 m and 10-50 m is considered as one of the channel properties and BER is captured for Eb/No varying from -10 to +10 db. From the results, it is concluded that proposed DTCWT-OFDM scheme achieves an improvement of 18.69 % and 77.6 % in terms of BER as compared with DWT-OFDM and FFT-OFDM respectively. An additional error occurring on transmitted bit can be withstood for 534 bits providing an increase in data rate when compared to all other modulation schemes.

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