Performance Evaluation of DFT-Spread OFDM and DCT-Spread OFDM for Underwater Acoustic Communication

Prashant Kumar
Electrical Engineering Department
Indian Institute of Technology Patna
Patna, India
prashant@iitp.ac.in

Preetam Kumar
Electrical Engineering Department
Indian Institute of Technology Patna
Patna, India
pkumar@iitp.ac.in

Abstract—**This paper presents a comparative study of discrete cosine transform (DCT) spread orthogonal frequency division multiplexing (OFDM) with discrete Fourier transform (DFT) spread OFDM, applied to an underwater acoustic (UWA) channel. The UWA channel is characterized as a frequency selective multipath fading channel with long delay spread. Energy compaction property of DCT works well in reducing the peak to average power ratio (PAPR) in UWA channel. It is also shown that DCT spread OFDM has lower computational complexity compared to DFT spread OFDM. The bit error rate (BER) performance has been evaluated for both the schemes. Simulation results show that DCT spread OFDM has a better performance than DFT spread OFDM in UWA channel. A novel scheme of using the null subcarriers to implement complex field repetitive coding in case of DCT spread OFDM is proposed to further reduce the BER.**

Keywords-Underwater acoustic communication; ODFM; DFT-SOFDM; DCT-SOFDM; BER; PAPR

I. INTRODUCTION

Underwater acoustic sensor networks (UWASNs) are designed to perform a wide range of tasks varying from environmental monitoring to gathering of oceanographic data, marine archaeology, and search and rescue operations. Acoustic communication has the low link quality and fast channel fluctuation, due to multipath signal propagation and time variability of the medium which severely limits the capacity. Reflections from ocean surface and bottom are the major reasons for multipath propagation. The three unique characteristics of underwater (UW) acoustic channel are frequency-dependent attenuation, severe multipath and low propagation speed of sound, around 1500 m/s. None of these features are nearly as profound in land-based wireless channels, which make underwater wireless communication quite difficult, and necessitates devoted system design. Acoustic signals are preferred as high-frequency radio signals attenuate fast, and optical signals generally scatter in ocean channel. The acoustic channel has a low data rate which is only several tens of kilobits per second for ranges under 1 km, and it has even lower data rates at longer distances [1],[2]. Since UWASNs are battery operated, lowering the transmission power may extend network life time but at the cost of increased bit error rate (BER), as signal to noise ratio (SNR) might not be high enough to ensure satisfactory information transmission. Low power consumption, good BER and minimal complexity are three critical factors for UWASN system design.

Multi-carrier modulation (MCM) is an alternative to overcoming the excess delay spread inherited in underwater acoustic channels. MCM has become popular in UWSNs for two reasons, first that a signal can be processed in a receiver with very little increase of noise or interference caused by linear equalization of a single carrier signal, and second that the long symbol duration produces a higher immunity to impulse noise and fast fades. OFDM transmits signals over multiple orthogonal sub-carriers simultaneously and performs robustly in harsh multi-path environments achieving reasonable spectral efficiency and supporting high data rate transmission. OFDM offers diversity gain in frequency selective channels. It uses the fast Fourier transform to multicarrier modulate a signal and thus can take advantage of advances in digital signal processing and digital circuitry [3],[4],[5]. Recently, zero-padded OFDM has been extensively investigated for high data rate UWA communication [3],[6],[7].

The transmit signals in an OFDM system can have high peak values in the time domain since many subcarrier components are added via an inverse fast Fourier transform (IFFT) operation. High peak to average power ratio (PAPR) is a major drawback of the scheme and ways of minimizing it and improving the BER performance have been thoroughly researched. PAPR reduction techniques are classified into the different approaches: clipping, coding, probabilistic scrambling, adaptive pre-distortion, and multi level orthogonal (MLO) spreading technique. The discrete Fourier transform (DFT) and discrete cosine transform (DCT) transforms constitute a set of good MLO codes. The DFT spread OFDM has been studied for both radio frequency (RF) and UW channels; whereas DCT spread OFDM has not as yet been studied for UW channel. In [8] it is mathematically proved that this method is effective in reducing the PAPR. In this paper the use of DCT spread OFDM for UWA communication is proposed and its performance is compared with the already existing results of DFTSOFDM [9] under similar conditions.

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

A novel scheme of using the null subcarriers to implement complex field repetitive coding in case of DCTSOFDM is proposed to further reduce the BER.

The rest of the paper is organized as follows. In section II, the signal processing operation of both DFT and DCT spread OFDM is described. Section III and IV discusses the system model and the underwater acoustic channel. Simulation results of both types of systems for underwater acoustic channel are given in section V. Section VI concludes the paper with a critical comparison of the two approaches to improve OFDM system performance for underwater communication.

II. CODE SPREAD OFDM

Spectral nulls are inevitable in frequency selective multipath channels like the UWA channel which can severely corrupt or cancel out the OFDM subcarriers that are in their vicinity, resulting in a loss of the symbols borne by these carriers. This eventually results in a non-reducing BER and bandwidth loss due to retransmission of lost information. Retransmission in case of long propagation delay channels like UWA channel is not a good idea. One common solution is the use of some form of forward error correction (FEC) technique. A different approach is to scatter the groups of data symbols over the entire bandwidth, a technique called code spread (CS) OFDM. CSOFDM combines the spreading gain of CDMA with OFDM [10]. The data symbols are spread across the entire subcarrier so that every individual subcarrier bears a linear combination of all the data symbols. This means that if many subcarriers are faded deeply, still it will be possible to recover the total transmitted symbols. This is an advantage over OFDM where symbol is lost if the subcarrier modulating it is deeply faded by the channel. After the channel treatment the spread symbols are easily separated using linear matrix operation. DCT function as spreading sequences is advantageous as it allows the use of the efficient DCT to spread and de-spread the data symbols, making the demodulation process simpler. This method helps in tackling frequency-selective fading and provides better performance in multipath fading environment.

In case of DFT spread OFDM, let the *2M* bit input data be $d_i, \{d_i, 0 \le i \le 2M-1\}$ and the corresponding symbols after mapping be: x_l, $\{x_l = d_{2(i-1)} + jd_{2i-1}, 0 \le l \le M-1\}$. On spreading by FFT operation, the spread symbols can be represented by S_k, $\{S_k = FFT(x_l)\}$

$$S_k = \sum_{l=0}^{M-1} x_l e^{-j2\pi lk/M} \tag{1}$$

These DFT spread symbols $\{S_k, 0 \le k \le M-1\}$ are mapped onto M subcarriers. Oversampling by a factor Q is used to approximate the true signals. The Q-time oversampled samples can be obtained by performing QM-point IDFT on the data block S_k with $(Q-1)M$ zero-padding.

$$X_k = \begin{cases} S_k, & 0 \le k \le M-1 \\ 0, & M \le k \le N-1 \end{cases} \tag{2}$$

where k denotes the k^{th} sub-carrier symbol. The resulting frequency domain symbols X_k are then transformed to the time-domain symbol sequence $\left\{ \hat{x}_n, 0 \le n \le N-1 \right\}$ by an IFFT operation.

$$\begin{aligned} X_n &= IFFT(X_k) \\ &= \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j2\pi\frac{nk}{N}} \\ &= \frac{1}{N}\sum_{k=0}^{M-1} S_k e^{j2\pi\frac{nk}{N}} \\ &= \frac{1}{N}\sum_{k=0}^{M-1}\sum_{l=0}^{M-1} x_l e^{j2\pi\frac{(n-Ql)k}{N}} \end{aligned} \tag{3}$$

It is interesting to note that at least half of the subcarriers are nulled, as if this is not done then the FFT spreading and the IFFT operation of OFDM would cancel each other. However such a spreading by DCT would not necessitate the nulling of subcarriers and hence all subcarriers would be useful and carry information. DFT is very popular due to its computational efficiency however; it has strong disadvantages of being complex and having poor energy concentration. Energy concentration is the property to pack the energy of a sequence into as small number of frequency coefficients as possible. If compaction is high, one only has to transmit a few coefficients. DCT proficiently de-correlates the transformed signal and the output contains the maximum variance in the least number of transform coefficients. DCT is a better transform, from energy compaction point of view. This ability is demonstrated by considering the 2-point transform:

$$X[0] = x[0] + x[1] \tag{4}$$

The first coefficient is the DC-value. An orthogonal transform can be written as

$$X = Tx, \tag{5}$$

$$X^T X = I; \ I \text{ is identity} \tag{6}$$

i.e. T has columns that are orthogonal hence

$$X[0] = x[0] - x[1] \tag{7}$$

If *x[0]* is similar to *x[1]*, then

$$X[0] = x[0] + x[1] \approx 2x[0] \tag{8}$$

$$X[1] = x[0] - x[1] \approx 0 \tag{9}$$

The even symmetric DCT or DCT II is the most popular one. The DCT of *x[n]* is defined as follows:

$$w[k] = \begin{cases} 1/2 & for \quad k = 0 \\ 1 & for \quad 1 \le k < N \end{cases} \tag{10}$$

$$C_x[k] = \begin{cases} \sum_{n=0}^{N-1} 2x[n]\cos\left(\frac{\pi}{2N}k(2n+1)\right), & 0 \le k < N \\ 0, & otherwise \end{cases} \tag{11}$$

$$x[n] = \begin{cases} \frac{1}{N}\sum_{k=0}^{N-1} w[k]C_x[k]\cos\left(\frac{\pi}{2N}k(2n+1)\right), & 0 \le n < N \\ 0, & otherwise \end{cases} \tag{12}$$

From above it becomes clear that DCT coefficients are real. On comparing DFT and DCT a simple relationship is obtained. Let there be a sequence *x[n]* which is zero beyond {0,...,N-1}, creating a new sequence:

$$y[n] = x[n] + x[2N-n-1]$$
$$= \begin{cases} x[n], & 0 \le n < N \\ x[2N-n-1], & 0 \le n < 2N \end{cases} \tag{13}$$

Now computing *2N*-point DFT of *y[n]*

$$Y[k] = \sum_{n=0}^{N-1} y[n] e^{-j\frac{2\pi}{2N}kn}, \quad 0 \le k < 2N \tag{14}$$

Rewriting as a function of N terms only

$$Y[k] = \sum_{n=0}^{2N-1} y[n] e^{-j\frac{2\pi}{2N}kn} + \sum_{n=N}^{2N-1} y[n] e^{-j\frac{2\pi}{2N}kn} \tag{15}$$

Now rewriting as a *N* terms function

$$Y[k] = \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi}{2N}kn} + \sum_{n=N}^{2N-1} x[2N-n-1] e^{-j\frac{2\pi}{2N}kn}$$

(m = 2N-1-n, n = 2N-1-m)

$$= \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi}{2N}kn} + \sum_{m=0}^{N-1} x[m] e^{-j\frac{2\pi}{2N}k(2N-1-m)}$$
$$= \sum_{n=0}^{N-1} x[n] \left\{ e^{-j\frac{2\pi}{2N}kn} + e^{j\frac{2\pi}{2N}} \underbrace{e^{-j\frac{2\pi}{2N}k2N}}_{1} e^{j\frac{2\pi}{2N}k} \right\}$$
$$= \sum_{n=0}^{N-1} x[n] \left\{ e^{-j\frac{2\pi}{2N}kn} + e^{j\frac{2\pi}{2N}kn} e^{j\frac{2\pi}{2N}k} \right\} \tag{16}$$

To express as cosine one has to convert into two mirror exponents, so writing as a function of *N* terms only

$$Y[k] = \sum_{n=0}^{N-1} x[n] \left\{ e^{-j\frac{2\pi}{2N}kn} + e^{j\frac{2\pi}{2N}kn} e^{j\frac{2\pi}{2N}k} \right\}$$
$$= \sum_{n=0}^{N-1} x[n] e^{j\frac{\pi}{2N}k} \left\{ e^{-j\frac{2\pi}{2N}} e^{-j\frac{\pi}{2N}k} + e^{j\frac{2\pi}{2N}kn} e^{j\frac{\pi}{2N}k} \right\}$$
$$= \sum_{n=0}^{N-1} 2x[n] e^{j\frac{\pi}{2N}k} \cos\left(\frac{\pi}{2N}k(2n+1)\right)$$
$$= e^{j\frac{\pi}{2N}k} \sum_{n=0}^{N-1} 2x[n] \cos\left(\frac{\pi}{2N}k(2n+1)\right) \tag{17}$$

$$Y[k] = e^{j\frac{\pi}{2N}k} C_x[k], \quad 0 \le k < 2N \tag{18}$$

$$C_x[k] = \begin{cases} e^{-j\frac{\pi}{2N}k} Y[k], & 0 \le k < N \\ 0, & otherwise \end{cases} \tag{19}$$

Basically the above analysis can be summarized in three steps:

$$\underbrace{x[n]}_{N-pt} \leftrightarrow \underbrace{y[n]}_{2N-pt} \underset{DFT}{\Leftrightarrow} \underbrace{Y[k]}_{2N-pt} \leftrightarrow \underbrace{C_x[k]}_{N-pt} \tag{20}$$

This interpretation explains why the DCT is able to concentrate energy and also gives a fast algorithm for computing DFT. The sequence *y[n] =x[n] + x[2N-1-n]*, is just an addition of a mirrored version of *x[n]* to itself. It is well known that DFT is identical to discrete Fourier series of its periodic extension. For periodic extension in case of DFT, we work with extension of *x[n]* and in case of DCT we work with extension of *y[n]*. It can be graphically shown that in DFT case discontinuities are introduced by extension which does not happen with DCT, because of symmetry of *y[n]*. The removal of this virtual discontinuity, containing high frequencies make DCT much more efficient. The interpretation also gives an efficient algorithm for DCT computation. There are three steps:

1) $Y[n] = x[n] + x[2N-1-n]$ (21)

2) $Y[k] = DFT\{y[n]\}$, (22)

which can be computed with a 2N-point FFT

3) $C_x[k] = \begin{cases} e^{-j\frac{\pi}{2N}k} \quad Y[k], & 0 \le k < N \\ 0, & otherwise \end{cases}$ (23)

thus complexity of *N*-point DCT is the same as the complexity of *2N*-point DFT [11].

III. System Model

The system model is similar to conventional OFDM but slightly modified by including an additional spreading block before the IFFT stage and another de-spreading block after the FFT stage. Both DFT and DCT block in the respective schemes spread information over several subcarriers which results in diversity gain in a frequency selective fading channel. The system model is shown in figure 1 and 2. Figure 3 shows the DCTSOFDM system which uses interleaver and repetitive coding to achieve better BER with the same complexity as that of DFTSOFDM. The input data bit stream pass through a serial to parallel converter which converts them into desired N_b data symbols, QPSK modulation is used for mapping. The symbols are then spread into N_c parallel spread symbols. For fully loaded case where $N_b=N_c$, the number of OFDM carriers used, the data symbol vector $S=[S1,...,S_{Nb}]$ is simply multiplied by a spreading matrix of size N_c x N_c. In the partially loaded case where $N_b<N_c$, zero padding is done. The obtained spread symbols are modulated onto N_c carriers by OFDM. Cyclic prefix of suitable length equal to the impulse response of the channel is prefixed to the beginning of each CSOFDM symbol prior to transmission.

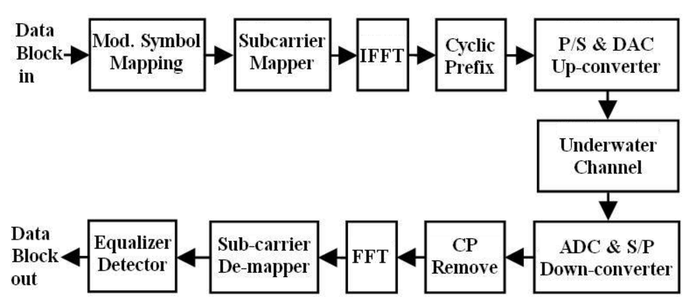

Figure 1: OFDM

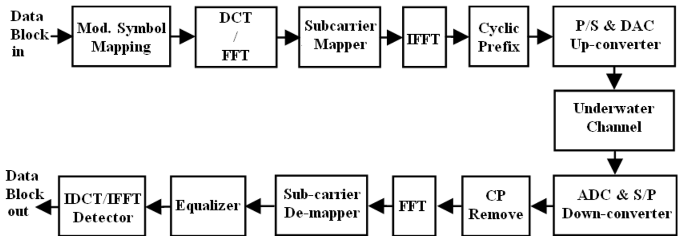

Figure 2: DCT/DFT spread OFDM

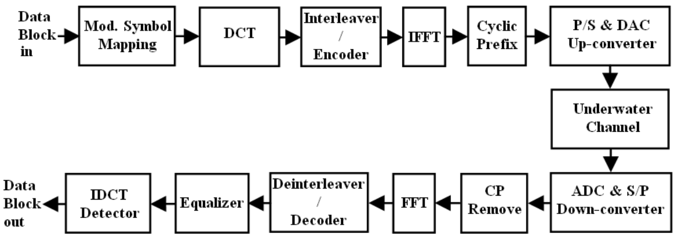

Figure 3: DCT spread OFDM with interleaver and repetitive encoder

IV. Underwater Acoustic Channel

The characteristic of underwater acoustic channel is a crucial factor in the efficient design of reliable and high data rate system. Past ocean experiments have shown that the UWA channel often exhibit worse performance than a Rayleigh fading channel modeling. Spatial-temporal correlation also has significant impact on the bit error rate performance of the channels. Shallow water acoustic channel has been modeled as a five path Rayleigh fading channel. Time variant fading has been incorporated and additive noise is built which is adopted from Rayleigh fading channel model [12],[13]. Multiplicative fluctuation of each individual path is realized by including a time variant and correlated fading factor in the signals amplitude or the power.

Additive white Gaussian noise (AWGN) is combined at the receiver. After conditioning and cyclic prefix removal demodulation of the received signal is done by FFT algorithm. Absolute channel state information is assumed at the receiver which has been implemented using matched filter. The final data bit is obtained after serial to parallel conversion of despread signal.

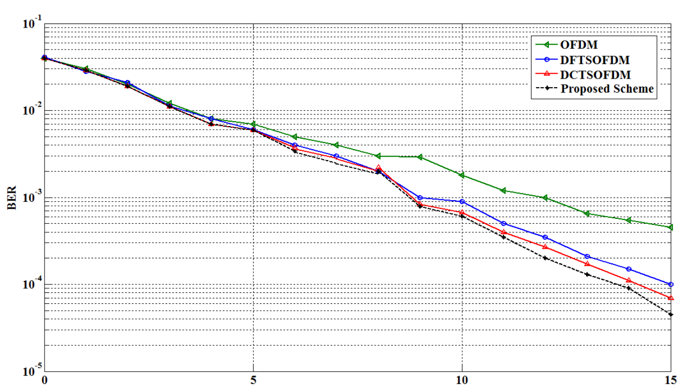

Figure 4: BER performance of OFDM, DFT-SOFDM, DCT-SOFDM and repetitive coded DCTSOFDM

TABLE 1: SYSTEM SPECIFICATION

Parameter	DFT-SOFDM	DCT-SOFDM
Mapping	QPSK	QPSK
IFFT point	2048	512
Useful subcarriers	512	512
Unused carriers	Zero padded	Nil
Signal frequency band	6 kHz/15 kHz	6 kHz/15 kHz
Carrier frequency	27 kHz/30 kHz	27 kHz/30 kHz
Cyclic prefix	25%	25%

V. Simulation Results

DFTSOFDM and DCTSOFDM are simulated in UWA channel. The system specifications are given in Table 1. The Matlab simulation results are shown in Figure 4. It is noteworthy that in extremely hostile UWA channel a signal to noise power ratio of 15dB is difficult to achieve at the receiver. For ordinary OFDM, the BER at 15dB is as high as 4.5e-4 and that of DFT-SOFDM is 1e-4. Result for DFTSOFDM matches with the existing result of [9] which validates the simulation. At a BER of 1e-4 DCTSOFDM has a SNR gain of about 1dB over DFTSOFDM. With almost same computational complexity and number of subcarriers; repetitive codes with code rate of less than or equal to ½ may be employed to get further BER reduction. DCT spread OFDM with repetitive code with code ratio ¼ is evaluated. The scheme is shown in figure 5 and is compared with the localized DFTSOFDM scheme proposed in [9] as shown in figure 6. At a SNR of 15dB the proposed scheme has a BER of 4.5e-5 where as DFTSOFDM has that of 1e-4. For a BER of 1e-4 the proposed scheme offers a SNR gain of further 1dB.

The power spectral density (PSD) for both the systems at transmitter is plotted and shown in figure 7 and 8. The PSD of the receive data is shown in figure 9 and 10.

Figure 11 shows the complementary cumulative distribution (CCDF) versus PAPR plot for both DFTSOFDM and DCTSOFDM with respect to OFDM, which confirms that the latter has a slightly better performance.

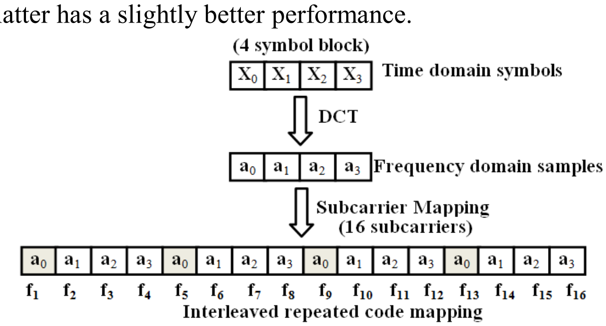

Figure 5: Schematic of proposed DCTSOFDM

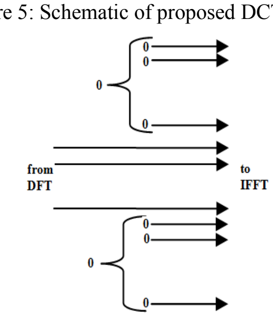

Figure 6: Localized DFTSOFDM proposed in [9]

VI. CONCLUSION

This paper evaluated the DCT spread OFDM system, a technique that overcomes the fading effects of underwater acoustic channel nulls by spreading the modulated symbols across the bandwidth before OFDM. It has been shown that DCT spread OFDM has a better BER and PAPR performance than DFT spread OFDM. It has also been shown that DCT spreading has a lower computational complexity than DFT spreading. Hence DCT spread OFDM is a potential candidate for future underwater acoustic communication.

REFERENCES

[1] M. Stojanovic and J. Presig, "Underwater acoustic communication channels: Propagation models and statistical characterization," IEEE Communications Magazine, IEEE , vol.47, no.1, pp.84-89, January 2009

[2] J. Proakis, J. Rice, E. Sozer, and M. Stojanovic, "Shallow water acoustic networks," in Encyclopedia of Telecommunications, J. G. Proakis, Ed. John Wiley and Sons, 2003.

[3] M. Stojanovic, "Low Complexity OFDM Detector for Underwater Acoustic Channels," OCEANS 2006, vol., no., pp.1-6, 18-21 Sept. 2006.

[4] M. Stojanovic, "OFDM for Underwater Acoustic Communications: Adaptive Synchronization and Sparse Channel Estimation," in Proc. ICASSP, 2008.

[5] B. Li, S. Zhou, M. Stojanovic, L. Freitag, J. Huang, and P. Willett, "MIMO-OFDM over an Underwater Acoustic Channel," OCEANS 2007, vol., no., pp.1-6, Sept. 29 2007-Oct. 4 2007.

[6] B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, "Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts," IEEE J. Ocean. Eng., vol. 33, no. 2, Apr. 2008.

[7] C. R. Berger, S. Zhou, J. Preisig, and P. Willett, "Sparse channel estimation for multicarrier underwater acoustic communication: From subspace methods to compressed sensing," Signal Processing, IEEE Transactions on , vol.58, no.3, pp.1708-1721, March 2010.

[8] Sun Shanlin; Hou Chunping; Yan Lei; Fu Jinlin; , "A Novel Method Based DCT to Reduce PAPR of OFDM Systems," Wireless Communications, Networking and Mobile Computing, 2008. WiCOM' 08. 4th International Conference on , vol., no., pp.1-5, 12-14 Oct. 2008.

[9] Yonghuai Zhang, Haixin Sun, En Cheng, and Weijie Shen, "An Underwater Acoustic Implementation of DFT-Spread OFDM," EURASIP Journal on Advances in Signal Processing, vol. 2010, Article ID 572453, 6 pages, 2010.

[10] Al-Mahmoud, M.; Zoltowski, M.D.; , "Performance evaluation of Code-Spread OFDM using Vandermonde spreading," Radio and Wireless Symposium, RWS '09. IEEE , vol., no., pp.320-323, 18-22 Jan. 2009.

[11] The Transform and Data Compression Handbook, edited by K. R. Rao and P. C. Yip, CRC Press, 2001.

[12] M. C. Domingo, "Overview of channel models for underwater wireless communication networks," Physical Communication, vol. 1, no. 3, pp. 163–182, 2008.

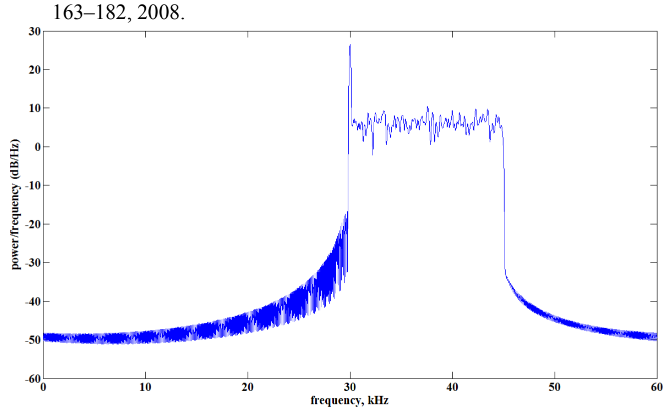

Figure 7: PSD of DFTSOFDM at transmitter

[13] Zielinski, A,; Young Hoon Yoon; Lixue Wu, "Performance analysis of digital acoustic communication in a shallow water channel", Oceanic Engineering, IEEE Journal of , vol.20, no.4, pp.293-299, Oct 1995.

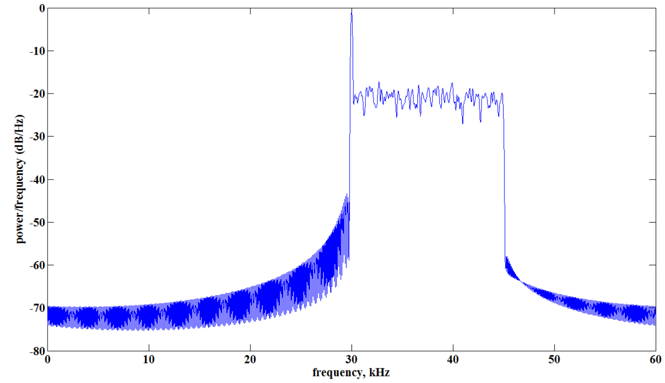

Figure 8: PSD of DCTSOFDM at transmitter

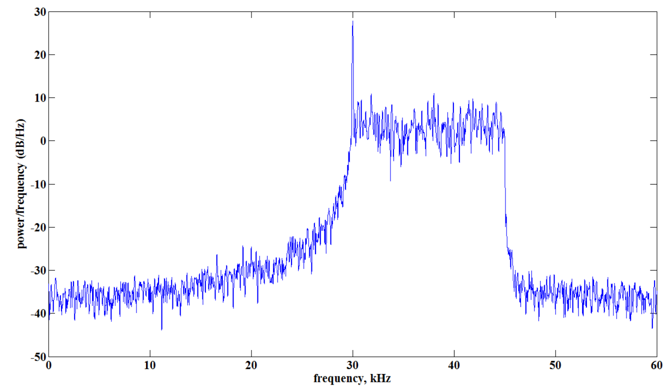

Figure 9: PSD of DFTSOFDM at receiver

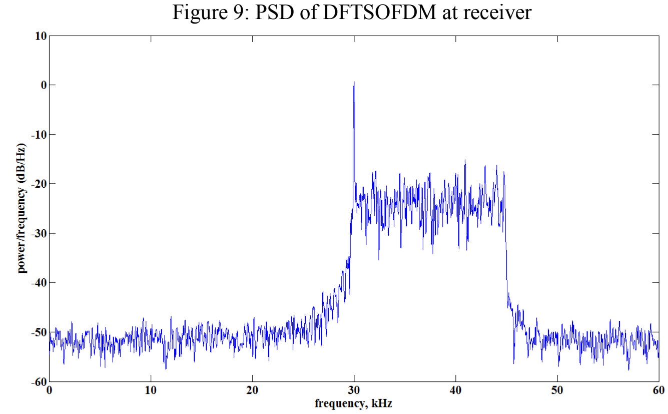

Figure 10: PSD of DCTSOFDM at receiver

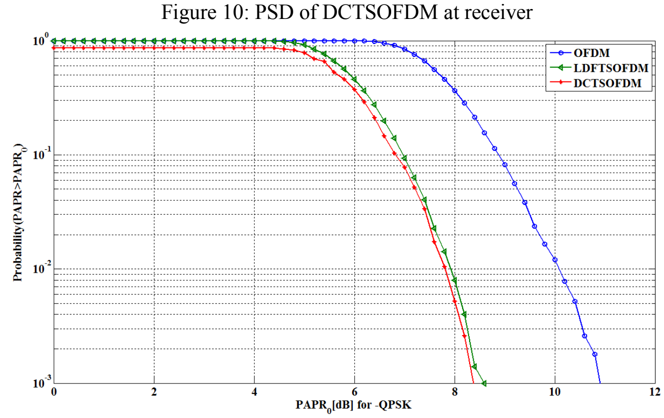

Figure 11: CCDF of localized DFTSOFDM and DCTSOFDM