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Comparative Study of DCT-and DHT-based OFDM Systems over Doubly Dispersive Fading Channels

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Abstract— *In high-mobility operating scenarios Orthogonal Frequency Division Multiplexing (OFDM) system lacks its optimality, intercarrier interference (ICI) occurs and the doppler shifts deteriorate the orthogonality of the subcarriers. However, this problem can be overcome by utilizing complicated equalizers at the receiver. Discrete Cosine Transform (DCT) and Discrete Hartley Transform (DHT) have been used instead of Discrete Fourier Transform (DFT) in the standard OFDM system. The performance results achieved enhancement over dispersive selective channels that cannot be accomplished with a standard OFDM system, even with utilizing complex equalizers. In this paper, the performance of the DCT-based OFDM system and DHT-based OFDM system is compared and analyzed with respect to DFT-based OFDM system performance over doubly dispersive fading channel at various doppler shifts, the block diagrams of the proposed systems are provided to simplify the theoretical analysis by making it easier to follow. Simulation results emphasized that the performance of DCT and DHT-based OFDM systems under doubly dispersive fading conditions scenario outperforms DFT-based OFDM system of order 3 dB energy per bit to noise power spectral density ratio (E_b/N_0).*

Keywords— *OFDM, ICI, DFT, DCT, DHT, E_b/N_0 , doubly dispersive channels.*

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a communication technique that gains more importance in wireless communication systems such as WLAN and WMAN with IEEE 802.11 and 802.16 standards, respectively. The 4th generation (4G) of mobile cellular communication, broadcasting applications like DVB-T are other examples of OFDM applications in wireless communication systems [1]. OFDM technique has a superior performance in canceling inter-symbol interference (ISI) without explicit knowledge of channel state information (CSI). Moreover, OFDM technique is able to cancel inter-carrier interference (ICI) using a single tap equalizer [2],[3].

Under the dispersive selective channel (frequency selective), as it is the case in a wireless channel under moving conditions, the OFDM system loses its optimality and the need for complex equalizer arises [4]. In [5] since the channel frequency response is rapidly time-varying; the optimal transmission/reception methodology should be able to process non-stationary signals. The Discrete Cosine Transform (DCT) is used instead of DFT into the conventional OFDM system under flat fading channels, and superior performance has been reported in [6]. DFT-OFDM requires complex equalization as doubly channel matrix, But the power leakage in the close sub-diagonals can be concentrated. Various techniques for the frequency domain equalization, including Zero Forcing (ZF), Minimum Mean Square Error (MMSE) [7], and Successive

Interference Cancellation (SIC) [8],[9], were suggested. In all schemes, Equalizer complexity can be reduced by using an approximate band structure of the frequency domain channel matrix [10],[11].

Likewise, the Discrete Hartley Transform (DHT) was used rather than DFT-OFDM and better efficiency was noticed under dispersive selective channels and superior performance has been reported in [12].

In this paper, it is suggested that a DCT-based OFDM system can be built rather than using an DFT-OFDM system over doubly dispersive fading channel effects. Their efficiency is observed at various doppler shifts. Moreover, with the same specifications, DHT-based OFDM system performance is compared to both DCT-based OFDM system and conventional DFT-based OFDM system.

This paper is organized as follows: DFT-based OFDM system is discussed in section II. DCT-based OFDM system is explained in section III. DHT-based OFDM system is introduced in section IV. Doubly dispersive fading channel characteristics are explained in section V. In section VI, simulations are performed and the performance of the proposed schemes is measured and analyzed. Finally, section VII concludes the paper.

II. DFT-BASED OFDM SYSTEM

A. The Discrete Fourier Transform (DFT)

Discrete Fourier Transform (DFT) converts a finite sequence of equally-spaced samples of a function into a same-length sequence of equally-spaced samples of the discrete-time Fourier transform (DTFT), which is a complex-valued function of frequency. The DFT is the most appropriate discrete transform utilized in many practical applications to perform Fourier analysis.

DFT changes a sequence of N complex numbers $\{x_n\} = x_0, x_1, x_2, \dots, x_{N-1}$ into another sequence of complex numbers $\{X_n\} = X_0, X_1, X_2, \dots, X_{N-1}$, which is defined as:

$$X_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n \cdot e^{j\frac{2\pi}{N}kn}$$
$$= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n \cdot \left[\cos\left(\frac{2\pi}{N}kn\right) + j \cdot \sin\left(\frac{2\pi}{N}kn\right) \right] \quad (1)$$

where k takes integer values from $\{0, \dots, N\}$.

B. The OFDM System

OFDM is a technique of multicarrier modulation, where the entire channel is subdivided into several narrow-band sub-channels, which broadcast in parallel in order to achieve high-data-rate transmission not withstanding enlarging the duration

of the signal to dispose of ISI. A cyclic prefix (CP) or guard intervals (GI) - ensuring distinct transmissions do not interfere with one another - is essential to guard the OFDM system against inter-carrier interference (ICI), which is caused by the remote channel delay spread. The standard DFT-based OFDM system block diagram is shown in Fig. 1.

The complex symbols $\{s_{n,k}\}_{k=0}^{N-1}$ with variance $E|s_{n,k}|^2 = \sigma_s^2$, which is transmitted at the n^{th} OFDM block, then the OFDM modulated signal can be represented as:

$$S_n(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_{n,k} e^{j2\pi k \Delta f t}, \quad 0 \leq t \leq T_s \quad (2)$$

where T_s is the symbol duration, Δf is the subchannel space, and N is the number of sub-channels of OFDM. The symbol period of the receiver should be adequate to modulate the OFDM signal in such a way that $T_s \Delta f = 1$ which is known as the orthogonal condition since it makes $e^{-j2\pi k \Delta f t}$ Orthogonal to each other for different k .

If there is no channel distortion, the orthogonal state of the transmitted symbols $s_{n,k}$ can be defined at the receiver as:

$$S_{n,k} = \frac{1}{T_s} \int_0^{T_s} S_n(t) e^{-j2\pi k \Delta f t} dt \quad (3)$$

The sampled version of the sampled OFDM signal baseband $S_n(t)$ in (2) can be written as:

$$\begin{aligned} s_n\left(m \frac{T_s}{N}\right) &= \sum_{k=0}^{N-1} s_{n,k} e^{-j2\pi k \Delta f m \frac{T_s}{N}} \\ &= \sum_{k=0}^{N-1} s_{n,k} e^{-j2\pi \frac{mk}{N}}, \quad t = m \frac{T_s}{N} \end{aligned} \quad (4)$$

where m is the sample index.

Equation (4) is identical to Inverse Discrete Fourier Transform (IDFT) of the transmitted symbol $\{s_{n,k}\}_{k=0}^{N-1}$. Thus, it is straightforward to demonstrate that the process of demodulation can be performed using DFT instead of integral in (3).

A cyclic prefix CP is essential for OFDM system to protect it from Inter Carrier Interference (ICI) that is caused by the delay spread of remote channels. Generally, CP is embedded in the adjacent OFDM blocks. If the CP length is greater than or equal to the delay spread of the channel, ISI will now be deleted [8]. Without the CP, the OFDM symbol length is T_s . while, by using CP, the time for the transmitted signal is reached $T = T_g + T_s$ and the OFDM symbol can be expressed as:

$$\tilde{s}_n = \sum_{k=0}^{N-1} s_{n,k} e^{-j2\pi k \Delta f t}, \quad -T_g \leq t \leq T_s \quad (5)$$

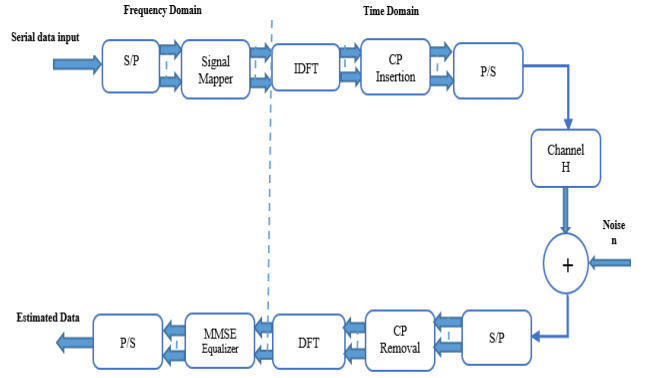


Fig. 1. DFT-based OFDM system block diagram

III. DCT-BASED OFDM SYSTEM

DCT is a Fourier-related transform like a DFT with real numbers only. DCT expresses signals for the complete cosine function that oscillates at various frequencies [6].

In this paper, we introduced a standard scheme DCT-based OFDM system, as shown in Fig. 2. The suggested scheme resembles the DCT-based OFDM system by displacing DFT block with DCT block in reception path. Similarly, IDFT block is replaced with IDCT block in transmission path.

DCT-based OFDM system is composed of a considerable orthogonal co-sinusoidal functions which is defined as[6]: $\varphi_n = \cos(2\pi f_n t)$, $0 \leq t < T$, $n = 0, 1, \dots, N-1$. Under the constraint that only real valued signals are transmitted, the minimum spacing of the subcarrier is supported at $\left(\frac{1}{2T}\right)$ Hz instead of $\left(\frac{1}{T}\right)$ Hz in DFT-based OFDM system by adopting co-sinusoidal orthogonal functions $\cos\left(\frac{2\pi n t}{2T}\right)$. The DCT-OFDM signal baseband is defined as:

$$x(t) = \sum_{n=0}^{N-1} X_n \cos\left(\frac{\pi n t}{2T}\right), \quad n = 0, \dots, N-1 \quad (6)$$

The proposed designed system is modulated and demodulated using DCT and Inverse DCT (IDCT) processes respectively, where the discrete-time representation is characterized as:

$$x(k) = \sqrt{\frac{2}{N}} \sum_{n=0}^{N-1} X_n B_n \cos\left(\frac{\pi n(2k+1)}{2N}\right), \quad k=0, \dots, N-1 \quad (7)$$

where

$$B_n = \begin{cases} \sqrt{\frac{1}{2}}, & n = 0 \\ 1, & k = 1, \dots, N-1 \end{cases} \quad (8)$$

In addition, the corresponding frequency-domain signal is given by:

$$\begin{aligned} X_{DCT}(n) &= \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} x_{DCT}(k) B_k \cos\left(\frac{\pi n(2k+1)}{2N}\right), \\ n &= 0, \dots, N-1 \end{aligned} \quad (9)$$

The Inverse Discrete Cosine Transform (IDCT) representation is defined as:

$$X_{IDCT}(n) = \frac{2}{N-1} \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} x_{DCT}(k) B_k \cos\left(\frac{\pi n(2k+1)}{2N}\right) \quad (10)$$

The DCT-based OFDM system has the following advantages [13]:

- 1- The DCT foundation has excellent properties of spectral compaction and energy concentration.
- 2- Less resilient to offset frequency as it has less ICI power leakage to adjacent subcarriers than OFDM.
- 3- The DCT uses only real arithmetic, reducing almost twice the complexity/ power consumption of DFT signal processing.

DCT-based OFDM system key drawbacks are that the channel impulse response needs to be symmetrically pre-filtered at the receiver to be diagonalized with symmetry using symmetrical guard sequence and pre-filter designs, and the DCT-based OFDM system cannot accommodate the complex signal without any ambiguity in the system due to its real arithmetic existence [14].

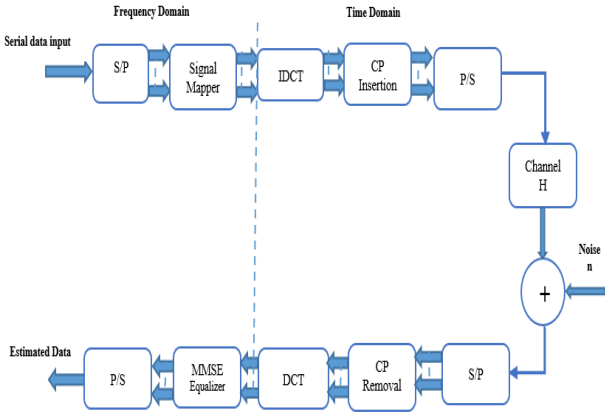


Fig. 2. DCT-based OFDM system block diagram

IV. DHT-BASED OFDM SYSTEM

The transformation of Hartley is an integral transformation closely related to Fourier transform, which transforms real-valued functions into real-valued functions (instead of requiring complex numbers) [2]. The transformation of a function $f(t)$ to Hartley is defined as following:

$$\mathbf{X}_{DHT}(\omega) = \frac{1}{\sqrt{2\pi}} \int_0^{T_s} f(t) \text{cas}(\omega t) dt \quad (11)$$

where

$$\text{cas}(t) = \cos(t) + \sin(t) = \sqrt{2} \cos\left(t - \frac{\pi}{4}\right) = \sqrt{2} \sin\left(t + \frac{\pi}{4}\right)$$

and ω is the angular frequency. The Hartley transformation has the convenient property of being its own inverse: DHT and its inverse IDHT have the same transform description in which the DHT of a real sequence $\mathbf{d} = [d_0 \ d_1 \ \dots \ d_{N-1}]^T$ and its inverse is given as follows:

$$\begin{aligned} x_n &= \sum_{k=0}^{N-1} d_k \text{cas}\left(\frac{2\pi kn}{N}\right), \quad 0 \leq n \leq N-1 \\ d_k &= \sum_{n=0}^{N-1} x_n \text{cas}\left(\frac{2\pi kn}{N}\right), \quad 0 \leq k \leq N-1 \end{aligned} \quad (12)$$

The DHT real orthogonal matrix is given utilizing cosine and sine matrix representation [15]. Let us define the (n, m) entries of $N \times N$ matrices \mathbf{C} and \mathbf{S} as follows:

$$c(m, n) = \cos\left(\frac{2\pi nm}{2N}\right), \quad 0 \leq n, m$$

$$s(m, n) = \sin\left(\frac{2\pi nm}{2N}\right), \quad 0 \leq n \leq N-1 \quad (13)$$

Consequently, the IDHT matrix can be described as:

$$\mathbf{X}_{IDHT} = \frac{1}{\sqrt{N}} (\mathbf{C} + \mathbf{S}) \quad (14)$$

Proving this is straightforward $\mathbf{X}_{DHT} \mathbf{X}_{IDHT} = \mathbf{I}_N$.

Following the same changes as in the DCT-based OFDM system architecture, the DHT-based OFDM proposed architecture is similar to the DFT-based OFDM one as shown in Fig. 3, except that the DHT block is used rather than the IDFT block on the transmitter and the DHT block instead of the DFT block on the receiver, which is one of the advantages of using the DHT as the basis for the OFDM system, i.e. both the transmitter and receiver use the same DHT hardware.

While DHT has less computational complexity than DFT and the DHT and its inverse IDHT are the same, there are two major problems with wireless communications for DHT-based OFDM.

First, since DHT is a real-established transformation, a one-dimensional (1D) modulation technique such as PAM and BPSK are considered. Second, due to the inherent properties of DHT, DHT-OFDM cannot directly diagonalize the multipath channel impulse response (CIR) [14,15].

From the perspective of BER vs. SNR, DHT-based BPSK-OFDM provides the same transmission performance as DFT-based BPSK-OFDM, but because it is only based on the real valued DHT, it requires less computational complexity and implementation expense. Additionally, because of its high "energy compaction" feature and real valued nature, the DCT based BPSK-OFDM performs better in terms of bit error rate (BER) than the DFT- and DHT based BPSK-OFDM systems [16].

The authors in [15] proposed a DHT-based OFDM system used a method that would diagonalize the equivalent matrix of the fading channel and apply 2-D modulation formats such as QPSK but with a more complicated system. A complicated equalizer is also required in dually selective channel fading scenarios such as DCT-based OFDM system.

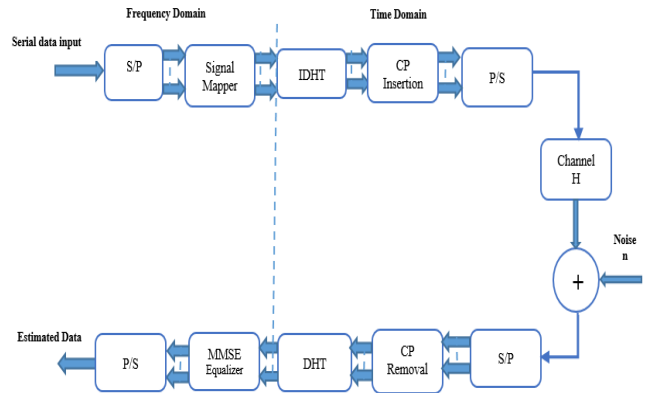


Fig. 3. DHT-based OFDM system block diagram

V. DOUBLY DISPERSIVE CHANNEL

Due to the changes in the propagation path induced by the movement between the transmitter and the receiver, the channel is time-varying for radio transmission applications. The rate of growth in these spreading conditions induces the fading rapidly (the rate of change in fading conditions).

Multipath effects are dependent on a range of variables, such as the presence of reflective objects in a continuously variable channel in the propagation system. The energy of some waves is distributed by reflection and dispersion, while a line of sight (LOS) comes directly to the recipient without any obstacles sometimes. Also, the distances traveled by each of the multi-track components. Multipath components with variable phases and amplitudes also lead to changes in signal strength.

If the received signal consists of more reflective beams and a large line-of-sight (non-fading) component, the amplitude of the envelope is Rician-density due to its small-scale fading and Rician fading, as is the case in highways and small villages. The Rician power density function is approached with the Rayleigh power density function as the amplitude reaches zero [17]. In other words, small-scale fading statistics, with a line of sight path being blocked, are said to be Rayleigh and Rician.

If processing of block-by-block is taken into account across a linear time-invariant (LTI) (within the block) frequency-selective noisy channel, the symbols are obtained accordingly:

$$r_n = H_n F^* s_n + n_g \quad (15)$$

where r_n is defined as the received sequence, H_n is the $N \times N$ channel matrix, F the DFT/DCT/DHT matrix, F^* is the IDFT/IDCT/DHT matrix, s_n is the transmitted data, and n_g is the Additive White Gaussian Noise (AWGN) in the time domain. After demodulation using DFT/DCT/DHT, the received vector \hat{r}_n is produced by:

$$\hat{r}_n = F H_n F^* s_n + F n_g \quad (16)$$

According to the cyclic prefix, H_n is a circulant under stationary conditions, and it tends to be decoupled by the DFT/DCT/DHT matrix. Because $F H_n F^*$ is a diagonal matrix, the received signal is evened out by essentially altering the amplitude and the phase of the received sequence [18]. In [19], the OFDM system splits the wide-band spectrum of the single carrier FDM system into several overlapping but orthogonal narrowband sub-channels and thus covers the frequency selective channel almost into non-frequency selective sub-channels. If the frequency fading happens within the desired bandwidth, each sub-channel frequency response can be roughly regarded as constant. The multi-path fading channel can, therefore, be compensated via a single-tap equalizer, which is so simple. However, the usage of CP by duplicating the last part of an OFDM symbol as its OFDM systems is immune to a multi-path fading compared with single carrier systems [20].

Since, time-frequency-selective (dispersive selective channel) is typically found on the fast fading remote channel,

this common technique is not successful and the OFDM system requires a complex equalizer [21].

The change in channel fading often depends on the speed at which the recipient and/ or transmitter travels, in which the movement causes doppler to shift the received signal elements. When present, the doubly dispersive fading channel is considered as change in the fading channel frequently response due to the doppler shift in the fading channel. Calculations of doppler shifts are given by:

$$f_d = \left(\frac{\Delta v}{c} \right) f_c \quad (17)$$

where f_d is the doppler shift frequency, Δv is the velocity difference between the transmitter and the receiver, c is the light speed and f_c is the signal carrier frequency.

In Linear Time Variant (LTV) channel, the frequency-domain channel matrix H_n in (15) is neither constant nor diagonal over consecutive OFDM blocks. Therefore, both the ICI and the useful channel part change from block to block.

VI. SIMULATION AND RESULTS

In this section, the IEEE 802.11a standard system is considered to exhibit the proposed systems. The diagonalized channel characteristic can be checked for both DCT-based OFDM and DHT-based OFDM systems by observing the channel estimation results. In IEEE 802.11a standard, the quantity of utilized sub-carrier $N_a = 96$, $N = 128$, $l = 8$ where N_a is the valid data, N is the number of subcarriers, l is the CP data and $\Delta f = 20$ KHz is involved.

DCT- and DHT-based OFDM systems have been inspected at carrier frequency $f_c = 10$ GHz. In addition to that, the modulation of QPSK is required. The fading channels of doubly Rayleigh are simulated with a root-mean-square delay of $\sigma = 3$ and an exponential power delay profile.

A. DFT-based OFDM system performance at various doppler frequencies

The performance of the DFT-based OFDM system for different doppler frequencies measured from the relation between Bit Error Rate (BER) at various E_b/N_0 as shown in Fig. 4. It is clear that, at no doppler frequency $f_d = 0$ the channel environment is time invariant. The DFT-based OFDM system uses the single tap equalizer in this case which is perfect for the system simplicity and good in performance.

As the presence of doppler shift, DFT-based OFDM system performance decreases independently of the use of the complex MMSE Equalizers. Furthermore, as the doppler shift changes from zero to 75 Hz, the DFT-based OFDM system needs E_b/N_0 around (8) dB to reach the corresponding BER (10^{-3}).

BER performance in DFT-based OFDM with different values of doppler freq.

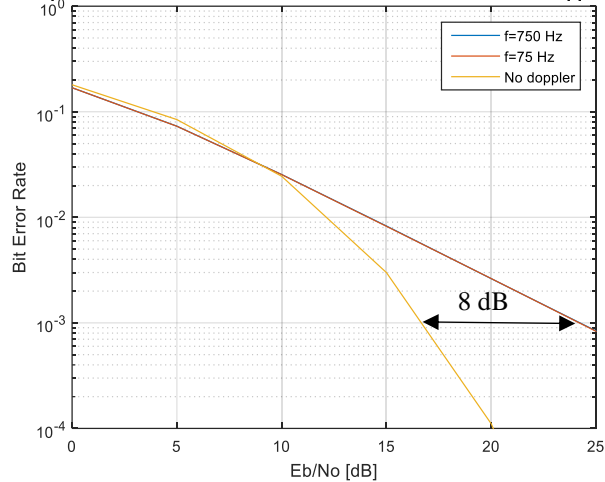


Fig. 4. BER performance of the DFT-based OFDM system at different doppler shift

B. DCT-based OFDM system performance at various doppler Frequencies

DCT-based OFDM system performance for various doppler frequencies are plotted at Fig. 5. It shows that, the system performance is better than that of the conventional DFT-based OFDM system, even though a simple single tap MMSE equalizer is used. Furthermore, it is clear that the DCT-based OFDM system is robust to the doppler shift. When the doppler shift varies from zero to 75 Hz, the DCT-based OFDM system needs E_b/N_0 (0) dB in order to reach the corresponding BER (10^{-3}).

BER performance in DCT-based OFDM with different values of doppler Freq.

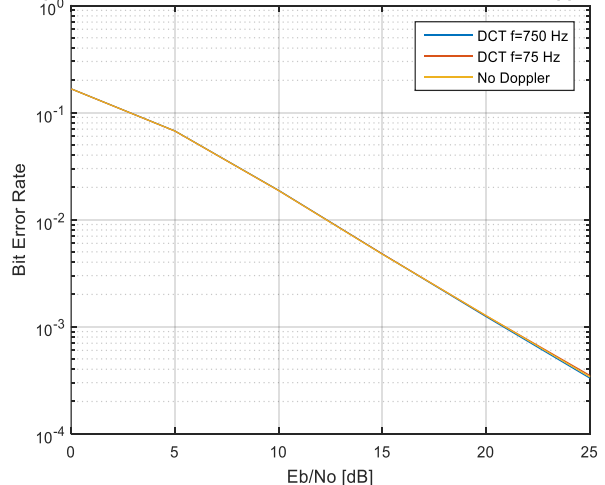


Fig. 5. BER performance of the DCT-based OFDM system at different doppler shift

C. DHT-based OFDM system performance at various doppler Frequencies

Fig. 6 shows the DHT-based OFDM system performance for various doppler frequencies. As shown in fig. 6, the system performance is better than that of the conventional DFT-based OFDM system, even though a simple single tap MMSE equalizer is used. Furthermore, it is clear that the DHT-based OFDM system is robust to the doppler shift. When the doppler shift changes from zero to 75 Hz, the DHT-based OFDM

system needs E_b/N_0 (0) dB in order to reach the corresponding BER (10^{-3}).

BER performance in DHT-based OFDM with different values of doppler Freq.

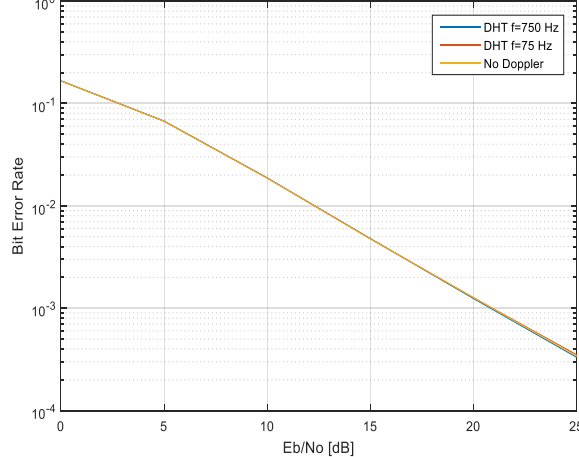


Fig. 6. BER performance of the DHT-based OFDM system at different doppler shift

D. Comparison between DFT-, DCT-, and DHT-based OFDM systems performance at the same doppler shift

BER performance of DFT-, DCT-, and DHT-based OFDM systems are measured using the same doppler shift parameter $f_d = 75$ Hz. As shown in fig. 7 below, both of the DCT-, and DHT-based OFDM systems have a better performance than DFT-based OFDM system. It is clear that, at the same doppler shift $f_d = 75$ Hz, the conventional DFT-based OFDM system needs E_b/N_0 around (3) dB to reach the corresponding BER (10^{-3}) achieved by using the DCT-, and DHT-based OFDM systems.

In addition to that, the BER performance of DCT-based OFDM system is little better than DHT-based OFDM system at the same doppler shift.

BER performance comparison bet. DFT-, DCT-, and DHT-based OFDM systems

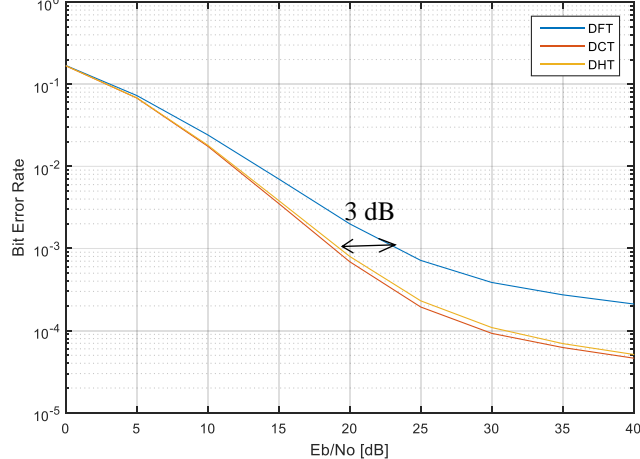


Fig. 7. BER performance comparison between DFT-, DCT-, and DHT-based OFDM systems

VII. CONCLUSION

In this paper, DCT-based OFDM system and DHT-based OFDM system had been used instead of conventional DFT-based OFDM system over doubly dispersive fading channel at

various doppler shifts. DFT-based OFDM system performance at fixed operation scenario (no doppler shift) is better than DCT-, and DHT-based OFDM systems. The degradation in the performance of DFT-based OFDM system under IEEE 802.11a standard in the mobility operation scenario had been noticed. The simulation results showed that the DCT-based OFDM system has a lower BER rate than the DFT-based OFDM system. The results have also shown that the DHT-based OFDM system is superior to DFT-based OFDM system. Simulation results emphasized that the performance of DCT and DHT-based OFDM systems under doubly dispersive fading conditions scenario approximately have the same performance that outperforms DFT-based OFDM system of order 3 dB energy per bit to noise power spectral density ratio (EB/N₀).

REFERENCES

- [1] T. Hrycak, and G. Matz, "Low-Complexity Time-Domain ICI Equalization for OFDM Communications Over Rapidly Varying Channels," in *Signals, Systems and Computers*, 2006, Fortieth Asilomar Conference on, 2006, pp. 1767-1771.
- [2] A. Solyman, and S. Weiss. J. J. Soraghan, "Low-Complexity LSMR Equalization of FrFT-Based Multicarrier Systems in Doubly Dispersive Channels," presented at the ISSPIT 2011, Bilbao, Spain, 2011.
- [3] H. -G. Yeh, S. and Charles C. Wang, " Parallel orthogonal frequency division multiplexed communication system," US patent, US7289425B2, October 2007.
- [4] I. Barhumi, G. Leus, and M. Moonen, "Equalization for OFDM over doubly selective channels" *IEEE Transactions on Signal Processing*, vol. 54, no. 4, pp. 1445 – 1458, april 2006.
- [5] M. Martone, "A multicarrier system based on the fractional Fourier transform for time-frequency-selective channels," *Communications, IEEE Transactions on*, vol. 49, pp. 1011-1020, 2001.
- [6] R. H. Alsisi, and R. K. Rao, "DCT- and FFT-based OFDM systems with Continuous Phase Modulation over Flat Fading channels", *International Conference on Electrical and Computing Technologies and Applications (ICECTA)*, 2017.
- [7] Y-S. Choi, P. J. Voltz, and F. A. Cassara, "On channel estimation and detection for multicarrier signals in fast and selective Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 49, pp. 1375–1387, Aug. 2001.
- [8] L. Rugini, and et al., "Simple equalization of time-varying channels for OFDM," *Communications Letters, IEEE*, vol. 9, pp. 619-621, 2005.
- [9] A. Fadaei Tehrani, H. -G. Yeh and S. -C. Kwon, "BER Performance of Space-Time Parallel ICI Cancellation of OFDM in MIMO Power Line Communications," *IEEE Systems Journal*, vol. 15, no. 2, pp. 1742-1752, June 2021.
- [10] G. Baruffa, and L. Rugini., "Improved Channel Estimation and Equalization for Single-Carrier IEEE 802.11ad Receivers" *Radioengineering*, vol. 32, no, 3, pp. 438-450, Sep. 2023.
- [11] H. -G. Yeh, S. Yildiz and R. Ren, " 4x1 Space-Time MIMO -OFDM Parallel Cancellation Schemes for Mitigating ICI," *IEEE Systems Conference (SysCon)*, pp. 1-6, April 2016.
- [12] M. Al-Gharably, and A. Almutairi, " Frequency-domain subcarrier diversity receiver for discrete Hartley transform OFDM systems," *Wireless Communications and Networking, EURASIP Journal*, article no. 78, 2019.
- [13] R. H. Alsisi, and R. K. Rao, "Performance of constant envelope DCT based OFDM system with Mary PAM mapper in AWGN channel", *IEEE International Systems Conference (SysCon)*, pp. 1-7, April 2017.
- [14] B. O. Haraand, and A. Petrick, *IEEE802.11 Handbook: A Designer's Companion*. New York: IEEE, 2004.
- [15] J. Chin-Kuo, and et al., "DHT-Based OFDM System for Passband Transmission Over Frequency-Selective Channel," *Signal Processing Letters, IEEE*, vol. 17, pp. 699-702, 2010.
- [16] Al-Gharably, M, and Almutairi, AF., "Frequency-domain subcarrier diversity receiver for discrete Hartley transform OFDM systems," *EURASIP Journal on Wireless Communications and Networking on*, vol. 78, March 2019.
- [17] C. Yang-Seok, and et al., "On channel estimation and detection for multicarrier signals in fast and selective Rayleigh fading channels," *Communications, IEEE Transactions on*, vol. 49, pp. 1375-1387, 2001.
- [18] A. Solyman, S. Elgamal, J. Soraghan, and S. Weiss, "Hybrid FrFT and FFT based Multimode Transmission OFDM System Based," *proceedings of the 8th ICEENG conference*, pp. 29-31, May 2012.
- [19] T. Kebede, and J. Steinbrunn, "Multi-Carrier Waveforms and Multiple Access Strategies in Wireless Networks: Performance, Applications, and Challenges," in *Global Telecommunications Conference*, vol. 10, pp. 21120-21140, March 2022.
- [20] L. Rugini, and P. Banelli, "Performance analysis of banded equalizers for OFDM systems in time-varying channels," in *Signal Processing Advances in Wireless Communications*, 2007. SPAWC 2007. IEEE 8th Workshop on, 200, pp. 1-5, 2007.
- [21] J. Won Gi, and et al., "An equalization technique for orthogonal frequency-division multiplexing systems in time-variant multipath channels," *Communications, IEEE Transactions on*, vol. 47, pp. 2732, 1999.