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Original Article

Performance Analysis of OTFS-based System using DWT, FFT and FrFT Transforms under Various Fading Environments

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Abstract - *The robustness of Orthogonal Time Frequency Space modulation in demanding communication contexts has attracted a lot of interest. To take advantage of the benefits that each transform offers in various areas of signal processing, this study explores the performance of OTFS modulation by combining a suite of distinct transforms, such as the Fractional Fourier Transform (FrFT), Fast Fourier Transform (FFT) and Discrete Wavelet Transform (DWT). Here, the OTFS signal is split up into many sub-bands using the DWT, which allows for a multi-resolution analysis that improves the system's flexibility in response to changing channel circumstances. This breakdown makes it easier to describe and work with signal components, which strengthens the signal's resistance to frequency-selective fading and lessens the effect of multipath propagation. To offer more options for modifying the signal in the t, and f domains, the FrFT is also used. The OTFS modulation may adapt to changing channel conditions and achieve tighter control over the signal characteristics by constantly optimizing its parameters using the flexibility of FrFT, which has been investigated. Here, the combined effects of several transforms on the SNR, BER, and overall performance of OTFS modulation are presented through a comprehensive performance study that includes simulations and assessments. The proposed systems were analyzed under various levels of PSK modulation, and the results that were obtained were studied for performance comparisons. The outcomes demonstrate the synergistic benefits of applying several transforms, offering insights into the complementarities and trade-offs that may be taken advantage of to improve the dependability and effectiveness of OTFS-based communication systems in a range of dynamic and varied situations. The proposed systems were operated under various fading environments, including AWGN, NAKAGAMI, and RICIAN channels.*

Keywords - *OTFS modulation, FFT, DWT, FrFT, Diverse transforms.*

1. Introduction

When it comes to supporting the high Doppler shifts that are anticipated in forthcoming wireless systems, such as 5G systems, which are expected to operate in millimetre wave (mm-Wave) bands and in high motion situations like high-speed trains, conventional systems that use the pulse shaping method fall short [1], with its appealing signalling attributes, the OTFS modulation, a newly suggested modulation format [2], can cater to the high-doppler signalling need by using a different methodology which is, signalling in the DD-domain rather than the more traditional t-f domain approach. The OTFS waveform is resistant to DD shifts in the wireless channel and has its roots in representation theory [2]. The goal is to perform modulation and detection in the DD domain by converting the time-dependent multipath link into a two-dimensional link. Over a diverse range of Doppler shifts, it has been demonstrated that OTFS exhibits significantly reduced block error rates compared to OFDM. The resilience to high-Doppler channels is particularly noteworthy, as OFDM performance gets badly affected in such high-Doppler scenarios [2]. The performance of the OTFS-based systems used for high-speed wireless communications has been analyzed here by implementing it with diverse transforms such as FFT, DWT and Fractional FrFT to see how the performance parameters such as BER and SNR vary when the system is subjected to multiple levels of modulation. These transforms have been seen to have improved the system performance when the same was applied to systems incorporating conventional multiplexing techniques such as OFDM, TDM and FDM. In this paper, the system using DWT transform was first implemented, and then its BER and SNR were evaluated when operating with 32, 64, 128, and 256-level Phase Shift Keying. The systems were also evaluated in various fading environments such as AWGN, RAYLEIGH, and RICIAN. Subsequently, the procedure under these levels of modulation and operated under these fading environments was analyzed for its performance using FrFT transform and FFT transform. A mutual performance analysis and comparison were done across various fading channels and across these diverse transforms to evaluate the best-case scenarios of the proposed OTFS system.

2. Literature Survey

Conventional multiplexing techniques such as OFDM have been analyzed and implemented using diverse transforms, and the most significant developments made in this area are summarised here. The BER of DWT and discrete Fourier transform-based OFDM systems is thoroughly estimated in [3]. They have established how SNR and BER for such systems vary upon increase in levels of modulation and upon changing the transforms[3]. An FrFT-attached OFDM system has been discussed in [4], and the suggested system's BER performance has been assessed in a variety of channel conditions, including AWGN, Rayleigh, Rician, and Nakagami, using 1024 levels of PSK and QAM modulations [4]. In [5], the Bit Error Rate (BER) performance of DWT-based OFDM systems, which is a substitute for conventional FFT-based OFDM systems, under the combined influence of channel loss, multipath fading, and lossy situations for mobile Wi-Max is analyzed [5], the findings showed that, for different modulation schemes, DWT–OFDM provides a reduced bit-rate error and better performance in mobile multipath situations [5].

Across multipath Rayleigh fading environment with exponential power delay profile, the functioning of Wavelet-based OFDM (WOFDM) is examined and contrasted with that of traditional OFDM [6]. The findings demonstrate that, for all SNRs, WOFDM performs better in terms of BER than traditional OFDM without Cyclic Prefix (CP) [6]; as it also provides greater bandwidth efficiency, WOFDM might be a viable substitute for traditional OFDM. A comparison was made between the wavelet-based and the Discrete Fourier Transform (DFT) based OFDM systems in terms of BER performance and PSD in [7]; the results concluded that Wavelet-based OFDM systems perform better in AWGN and Rayleigh fading channels in terms of BER comparisons. The use of Inverse DWT instead of Inverse FFT in the case of conventional OFDM has also been discussed, performance comparison of BER, PAPR and spectral efficiency was made between the two, and the results showed that with the same BER and Spectral efficiencies for both the systems, the wavelet-based OFDM system has reduced PAPR as compared to the one using IFFT.

The effectiveness of OFDM-based FrFT is examined, at various Doppler shifts using numerous fractional orders. The findings show that utilizing FrFT in place of Fourier Transform (FT) in an OFDM system improves processing, and without raising the transmit Signal-to-Noise Ratio (SNR), the same Bit Error Rate (BER) is reached, and processing gains of up to 3dB are realized for various Doppler frequencies. The effects of frequency offset in t-f selective fading channels are presented for OFDM systems based on fractional Fourier transform [8]. Results demonstrated that when carrier offset occurs in the scheme, or Doppler spread is similar to the inverse of the symbol duration, the FRFT-OFDM systems perform better in the frequency selective channel by selecting the ideal fractional factor [8]. The enhancement in the performance parameters of the OFDM system when implemented using DWT and FrFT has been evaluated under AWGN, RICIAN, RAYLEIGH and NAKAGAMI channels. The results conclude that better BER performance is obtained in DWT-FrFT attached OFDM when compared to conventional OFDM and FrFT appended OFDM. To provide a more effective technique for implementing OFDM systems, the study applies the wavelet SNR enhancement approach to the signal revival process of OFDM systems[9]; the improvement in SNR is validated by the obtained simulation results. The study in [5] examines the effectiveness of DWT-based OFDM systems in comparison to FFT-based OFDM systems when route loss, multipath fading, and noisy environments are all present, and the simulation results in [5] showed that, for different modulation schemes, DWT-OFDM promises to reduce BER and improve efficiency in mobile multipath situations.

In a performance comparison has been drawn between Wavelet-based OFDM systems and conventional OFDM systems. It was observed that wavelet-based OFDM can replace conventional OFDM systems in the future generation of communication systems. An FrFT-attached OFDM system has been proposed in [4]. To counteract the effects of multipath fading, the FrFT block has been added to the OFDM transmitter's output in the proposed system [4]; here, the BER performance has been assessed in a variety of channel conditions, including AWGN, Rayleigh, Rician, and Nakagami [4]. The work examines the performance of FrFT-based OFDM systems at various Doppler shifts with numerous fractional orders. The simulation results validated the improvement in system performance using FrFT.

The topic has been discussed in some of the most recent research articles that have been published, which intend to improve existing OTFS systems further. Some of these most recent articles have been discussed here. The paper [10] discusses various issues and challenges currently faced by OTFS systems and thereby draws an effective and detailed review of various related developments in OTFS. In [11], the PAPR analysis in OTFS modulation utilizing classical SLM is presented, and the outcomes are compared with those of OFDM modulation; it has been observed from the results that the classical SLM method can be an efficient approach for decreasing the PAPR in OTFS modulation. In [12], a BER analysis of OTFS systems was carried out in detail using various power allocation methods.

In [13], the performance of the DWT-based OFDM system is compared with the DFT-based OFDM system. The study concludes that while DFT-OFDM outperforms DWT-OFDM in the Rayleigh channel, their BERs in the AWGN channel are almost identical [13]. The implementation of FrFT in an advanced MIMO system based on OTFS has been proposed in [14], and the suggested FrFT-based channel estimation techniques outperform the current schemes in terms of NMSE, according to the simulation findings. The spectral efficiency of an OTFS-based system varies with interference, which is explained in [15].t has been verified that when the Doppler domain resolution is good, there is little loss in the OTFS SE performance [15]. In [16], the researchers have provided two preamble-based Orthogonal Time Frequency Space (OTFS) modulation algorithms for channel estimation; it was observed that in situations with noise and static multipath channels, these innovative techniques enable a reliable channel estimate. The study in [17] examines a DWT and non-positional arithmetic code mathematical model of signal processing. It has been predicted in this paper [17] that the transmission rate in OFDM systems will rise because of the application of this approach. To concurrently optimize communication and sensing capabilities, the researchers offer an ISAC framework in [18] that is based on the Weighted-type Fractional Fourier Transform Orthogonal Time Frequency Space (WFRFT-OTFS) waveform. It has been shown that this framework allows for flexible parameter adjustments.

The study in [19] proposes a Per-Wavelet Equalizer (PWEQ) that can be applied to any wavelet family and directly maximizes the Signal-to-Interference-plus-Noise Ratio (SINR) per symbol. It has been observed in [19] that at the expense of more computing complexity, the suggested PWEQ improves the SINR on the received symbols when compared to the TEQs. The OTCS-FrFT is presented in [20] as an expanded version of the OTFS modulation system. It has been demonstrated that the OTCS-FrFT, with fractional convolution, is resilient to time-varying channels with linear delays and Doppler spreading functions [20]. In [21], quadratic frequency modulation functions were implemented with FrFT, and performance was analyzed.

3. Research Gap

While going through the literature related to the implementation of these diverse transforms, it has been observed that not much has been done in exploring their implementation and utilization to OTFS systems, and no significant work has been done to establish the performance analysis of OTFS systems using these transforms and when operated under various fading environments, this leaves a potential research gap which has been explored and investigated in the proposed research work to establish how the OTFS system behaves under these conditions and how its performance is affected compared to conventional modulation techniques.

4. Proposed Methodology

Here, an OTFS system incorporating Discrete Wavelet Transform was first designed. The system was evaluated for its BER and SNR at with levels of PSK-modulation set at 32,64,128 and 256, as depicted in Table 1. Each system was individually operated under different fading channels like AWGN, NAKAGAMI and RICIAN. Then, the system was redesigned using FrFT and FFT at the aforementioned modulation levels, and again, the system BER and SNR were obtained under various fading environments, as mentioned above. The obtained results were analyzed and studied to draw performance comparisons across these diverse transforms and the levels of modulation as well as across the fading environments. The proposed system runs according to the following operating parameters.

Table 1. System parameters

Modulation Type	32,64,128 and 256 levels PSK
Fading Channels used	AWGN, RICIAN, NAKAGAMI
Parameters evaluated	BER, SNR
Transforms used	DWT, FrFT, FFT

5. Introduction to OTFS Modulation

Traditional modulation methods like OFDM have been challenged by the relatively recent modulation method known as orthogonal time frequency and space (OTFS). Even when used in situations with high Doppler and massive antenna arrays, this innovative modulation system supports the data symbols with nearly constant medium gain. A collection of 2D-orthogonal basis functions that cover the bandwidth and period of the data burst or packet are used by the OTFS system to modulate each information symbol in an OTFS transmission [2]. The block diagram can be used to demonstrate how an OTFS system functions in general, as shown in Figure 1.

Here, the signal is converted from the conventional Time and Frequency Domain to the Delay-Doppler domain by applying ISFFT and SFFT, which involves applying FFT in the Time Domain and IFFT in the Frequency Domain to translating the signal in the DD domain, thereby overcoming the shortcoming of High Doppler, ISI and Higher PAPR as seen in case of conventional modulation formats like OFDM.

6. Implementation of OTFS Modulation

The basic OTFS modulation works by first implementing the OTFS transform using the Heisenberg Transform [1] and then detecting it back using the Wigner Transform and, subsequently, the application of SFFT. The modulated symbols in OTFS can be defined in terms of OTFS transform as follows:

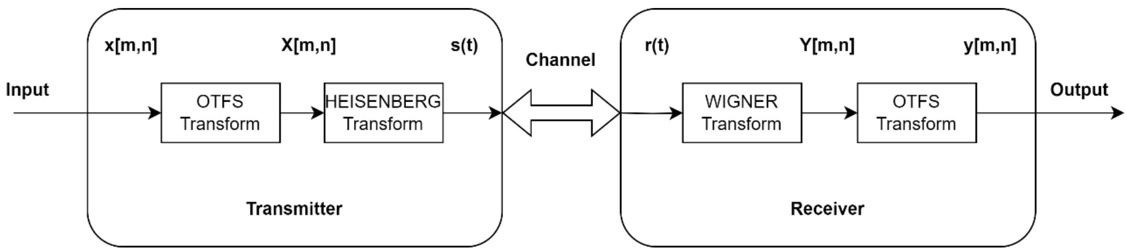


Fig. 1 OTFS Tx-Rx block diagram [2]

$$X[n, m] = W_{tx}[n, m]\, SFFT^{-1}(x[k, l]) \quad (1)$$

Equation (1) is what we call OTFS transform [B]. Here, x [k, l] represents a set of the information symbols that are represented in the DD domain (k, l), W_{tx} [n, m] represents the transmit windowing square summable function, which is used primarily for the multiplication of modulation symbols in Time-Frequency Domain. The transmitted signal may be obtained as shown in the block diagram using the Heisenberg Transform given as follows:

$$S(t) = \sum_{m=-\frac{M}{2}}^{\frac{M}{2}-1} \sum_{n=0}^{N-1} X[n,m].\, g_{tx}(t-nT)e^{j2\pi m\Delta f(t-nT)} \quad (2)$$

At the receiver end, the intercepted OTFS signal is demodulated by first applying Wigner Transform on it, which is given as:

$$Y[n, m] = A_{grx,\tau}(\tau; v)|_{\tau=nT,\, v=m\Delta f} \quad (3)$$

After the application of the Wigner transforms as per Equation (3), then apply the windowing function to obtain back the signal in its Time-Frequency domain and subsequently periodize it as shown in Equations (4) and (5), respectively as follows:

$$Y_W[n, m] = W_{rx}[n, m].\, Y[n, m] \quad (4)$$

$$Y_p[n,m] = \sum_{k,l=-\infty}^{\infty} Y_W[n-kN, m-lM] \quad (5)$$

Finally, the SFFT is applied to Equation (5) to obtain the signal in the DD domain, as shown below:

$$x[l, k] = y[l, k] = SFFT(Y_P[n, m]) \quad (6)$$

7. Discrete Wavelet Transform (DWT)

A mathematical method used in signal processing and picture reduction is called the Discrete Wavelet Transform (DWT). A signal is broken down into units known as wavelets that are localized in both the frequency and temporal domains. With varying degrees of detail, this decomposition offers a multi-resolution examination of the signal, encompassing both the high- and low-frequency components. The signal is divided into approximation and detail coefficients in turn by the DWT. The detail coefficients indicate finer details at various scales, while the approximation coefficients represent the signal's coarsest scale, capturing its general patterns. An iterative hierarchical decomposition can be used to provide a multi-level signal representation.

The Continuous Wavelet Transform (CWT) and the DWT are the two primary varieties of wavelet transformations. The DWT offers a discrete and computationally efficient method of signal analysis, making it very helpful in digital signal processing. The DWT is useful for analyzing non-stationary signals with variable frequency content because it can represent signals in both the t and f domains concurrently. The signal is filtered via several digital filters with varying sizes to produce the wavelet transform. By altering the signal's resolution, subsampling is used to carry out this scaling process [5]. The generation of such wavelets can be explained in Figures 2 and 3.

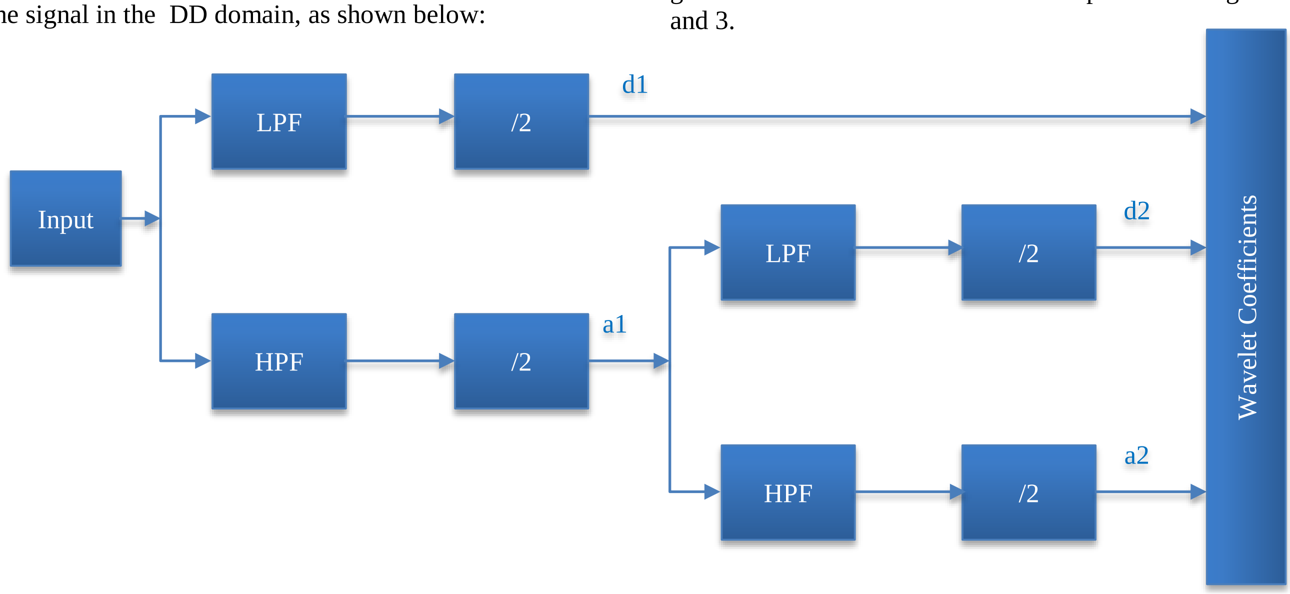


Fig. 2 Signal decomposition into wavelets [5]

In the breakdown, the input strings are divided into low-pass and high-ps sub-components, each of which has half as many samples as the prime string [5]. The DWT for the signal can be represented as follows:

$$X(m,k) = \sum_n x(n) 2^{\frac{m}{2}}\ \Psi(2^m \text{n-k}) \quad (7)$$

The transmitted symbol is constructed using the inverse wavelet transform [5]. Analyzing from wavelet coefficients is the term used to describe the reverse procedure of processing a signal using an inverse wavelet transform, which is usually described as synthesizing into wavelet coefficients. The reconstruction process of the signal from its coefficients can be explained using the following diagram.

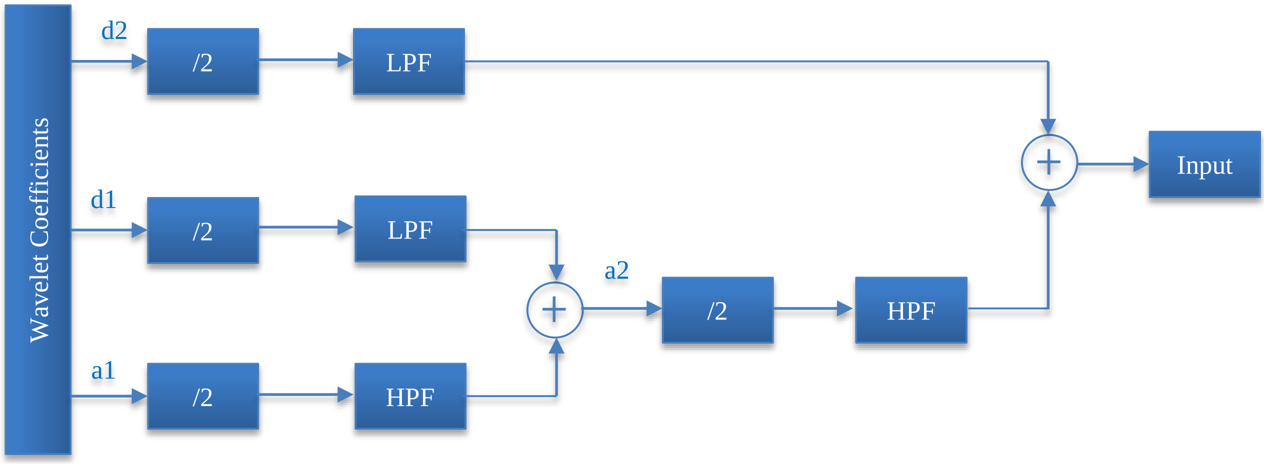


Fig. 3 Signal reconstruction from wavelets [5]

The reconstructed signal can be estimated using the following Equation.

$$X(n) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} X(m,k) 2^{m/2} \Psi(2^m \mathrm{n} - \mathrm{k}) \quad (8)$$

8. Fractional Fourier Transform (FrFT)

According to its definition, unified time-frequency transformation [4], or FrFT, is defined as the chirp basis expansion [4] that defines the rotation in the frequency plane of time. A generalization of the widely used Fourier Transform is the Fractional Fourier Transform (FrFT). The FrFT adds a parameter that permits the transformation to be carried out at a fractional angle as opposed to the set 90-degree angles used in the regular Fourier Transform, which breaks down a signal into its frequency components. The order or angle of rotation is represented by the parameter α, which defines the FrFT. The Fourier Transform (FrFT) equals the conventional Fourier Transform when α = 1. On the other hand, the FrFT offers an adaptable method for examining signal content in the time-frequency domain at other angles for varied values of α [1]. Mathematically, for a signal x(t), the FrFT is defined as follows:

$$X(\alpha, f) = \int_{-\infty}^{\infty} x(t). e^{-j\pi\alpha t^2} . e^{-j2\pi f t}\, dt \quad (9)$$

Equation (9) represents the FrFT of x(t) at an angle of α and frequency f.

Applications for the FrFT may be found in communication, optics, and signal processing. A more flexible representation of signals is made possible by it, particularly those with chirpy or non-stationary properties. The direction of the transform is determined by the value of α, which allows for more precise control over the analysis of signals in the combined time-frequency domain.

9. Fast Fourier Transform

An effective technique for determining the discrete Fourier transform and its inverse is the Fast Fourier Transform (FFT) algorithm. A signal or function can be transformed mathematically from its original domain-typically time or space-into the frequency domain. This process is called the Fourier transform. The frequency components that were present in the original signal are revealed by this modification. Conventional systems employ FFT at the reception side and IFFT (Inverse Fast Fourier Transform) at the transmitter side. To improve spectral efficiency and lower Inter-Symbol Interference (ISI), a cyclic prefix must be added at the transmitter side [22]. The basic function, known as the Discrete Fourier Transform (DFT), is the source of both the Fast Fourier Transform (FFT) and the Inverse Fast Fourier transform (IFFT). The implementing equation for FFT/IFFT can be derived from equations of Discrete Fourier Transform [22], which is given as follows.

$$X(k) = \sum_{n=0}^{N-1} X(n) e^{-j2\pi k / N} \quad (10)$$

Here, X(k)represents the DFT frequency output at the k-the spectral point where k ranges from 0 to (N-1). N is the total number of samples taken.

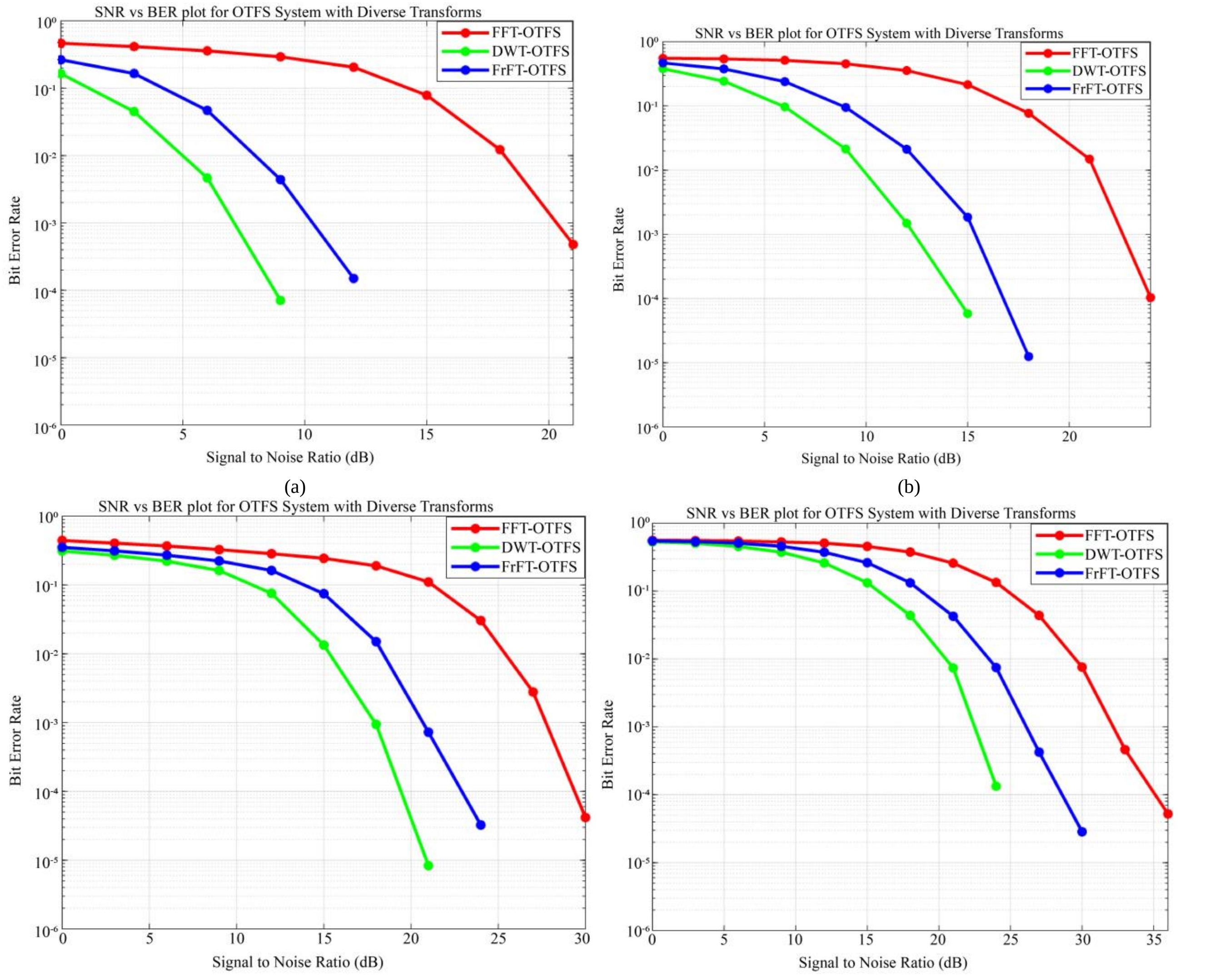
10. Experimental Setup

The proposed work was programmed using Matlab Version-2022; the process included first writing and designing the code for a general OTFS Trans-Receiver system using conventional Fourier Transforms, which include ISFFT at the transmission end and Heisenberg's Transform at the receiver end.

The system was then evaluated for performance with PSK modulation done at the transmitter side. Subsequently, the system was then re-programmed by replacing conventional Fourier transforms with DFT and the FrFT transforms, and again, it was evaluated for performance using multiple levels of modulation. The readings were recorded for diverse fading channels to compare the effects of fading channels on their performance.

11. Results and Discussions

The system was simulated with the aforesaid parameters to obtain the values of Signal to Noise ratios required against evaluated BER values. The simulation was carried out under the fading channels of AWGN, NAKAGAMI and RICIAN. The system was run with PSK modulation with levels set at 32, 64, 128, and 258. Three transforms have been implemented in the proposed OTFS system: FrFT, DWT, and the conventional FFT. The obtained results have been presented and discussed in this section.



(c) (d)

Fig. 4 (a) - (d): BER vs SNR using various transforms using AWGN fading at (a) 32PSK, (b) 64PSK, (C) 128PSK, and (d) 256PSK.

The obtained results are also presented in Table 2.

Table 2. Minimum SNR values required at BER of 10^{-4} using AWGN channel

Transform Used	32PSK	64PSK	128PSK	256PSK
FFT	>20dB	25dB	29.3dB	35dB
DWT	9dB	14.7dB	19.3dB	24.3dB
FrFT	12dB	17dB	23dB	28dB

From the results obtained, as depicted in Table 2, it was observed that the DWT transform provides the best performance for the proposed OTFS system out of all the implemented transforms. It was also observed that the SNR required to obtain BER of 10^{-4} increases as the modulation levels are increased, with 32-PSK requiring the minimum SNR while 256-PSK required the highest SNR. A significant improvement in SNR values was seen in the DWT-based system compared to other transforms with DWT-based system requiring SNR of just 9db compared to 12db and 20db, respectively, for FrFt and FFT-based systems when operated at 32-PSK. Out of all the implemented transforms, the order of performance under all levels of modulation is seen as DWT > FrFT > FFT. Also, with an increase in SNR, the BER values show a gradual decrease, as evident. Similarly, the results obtained for NAKAGAMI fading are presented in Figure 5.

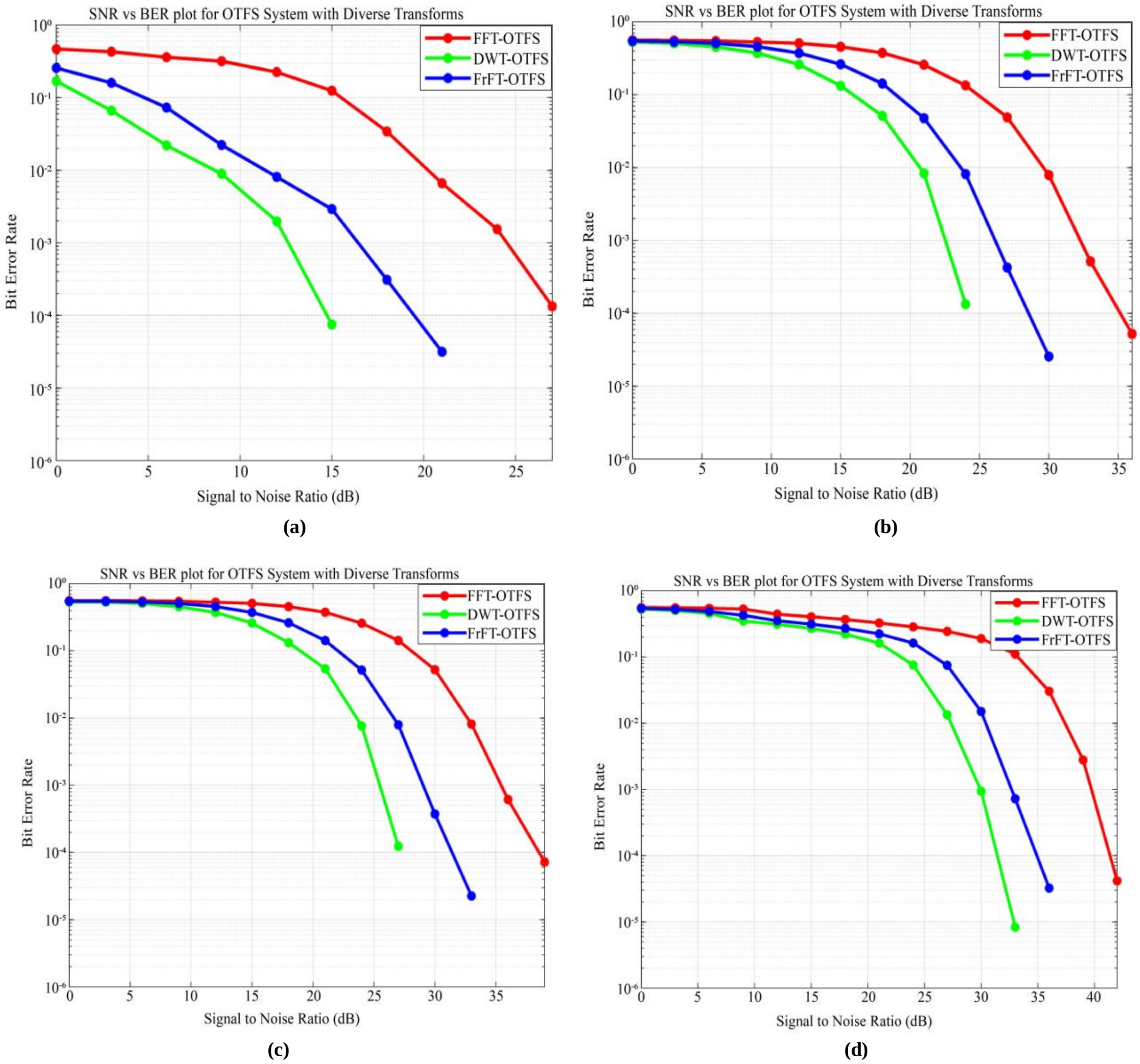


Fig. 5 (a) - (d): BER vs SNR using various transforms using NAKAGAMI fading at (a) 32PSK, (b) 64PSK, (c) 128PSK, and (d) 256PSK.

The obtained results are also tabulated in Table 3.

Table 3. Minimum SNR values Required at BER of 10^-4 using NAKAGAMI Channel

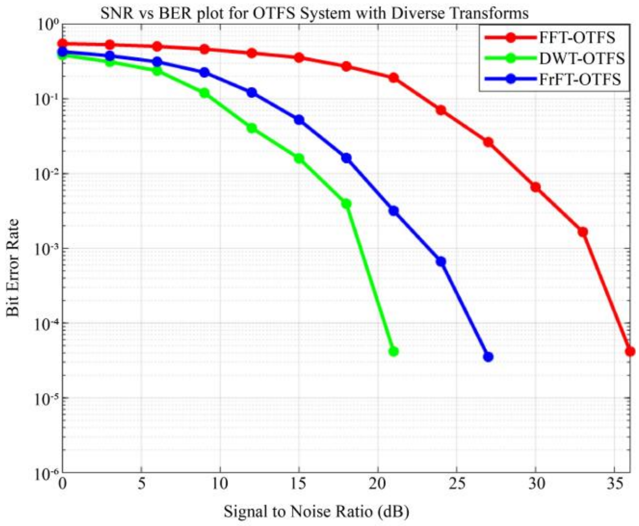
Transform Used	32PSK	64PSK	128PSK	256PSK
FFT	>27dB	35dB	39.3dB	41.5dB
DWT	14.8dB	24.7dB	26.5dB	31.5dB
FrFT	18.8dB	28dB	31.5dB	35dB

From the obtained results when the proposed system was implemented using the NAKAGAMI fading environment, it was observed that out of all the implemented transforms the DWT-based OTFS system performs the best.

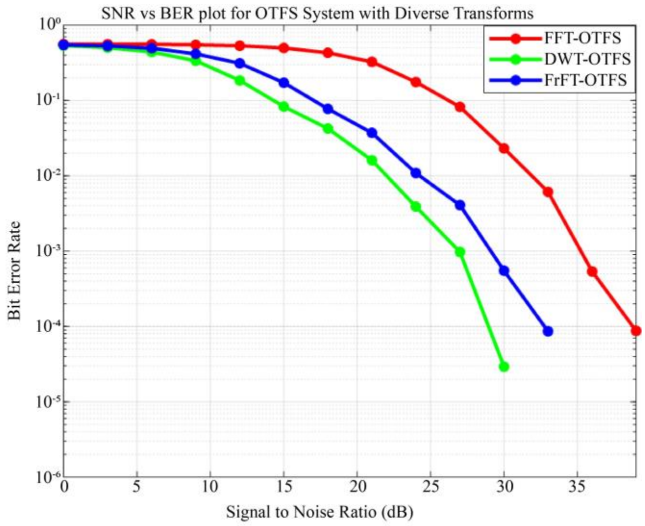
The required SNR values to yield acceptable BER values increased as the modulation levels were increased, with 32 PSK requiring the lowest SNR and 256 PSK requiring the highest SNR. In the case of DWT based OTFS system, a significant reduction in required SNR was seen as compared to FrFT and FFT-based OTFS systems, while DWT based OTFS system required a minimum SNR of 14.8db the FrFT and FFT-based OTFS systems require 18.8db and >27db approximately.

The minimum SNR required was seen for a DWT-based OTFS system at 32-PSK of approximately 14.8db, while the highest SNR was required for an FFT-based OTFS system with 256-PSK modulation of approximately 41.5db.

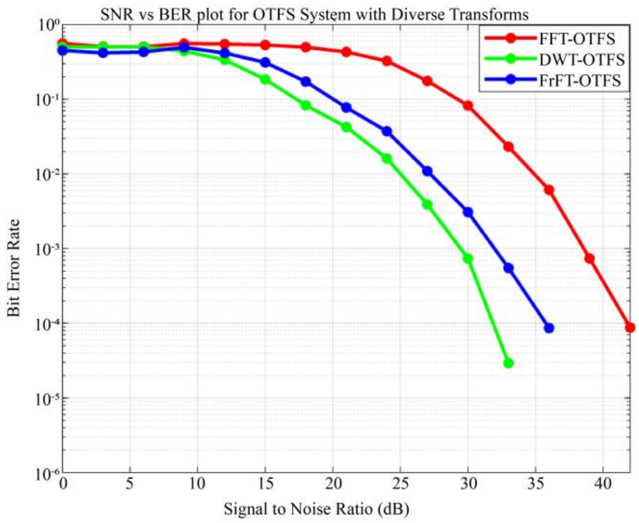
The system was also implemented using Rician fading channels, and the results are shown in Figure 6.



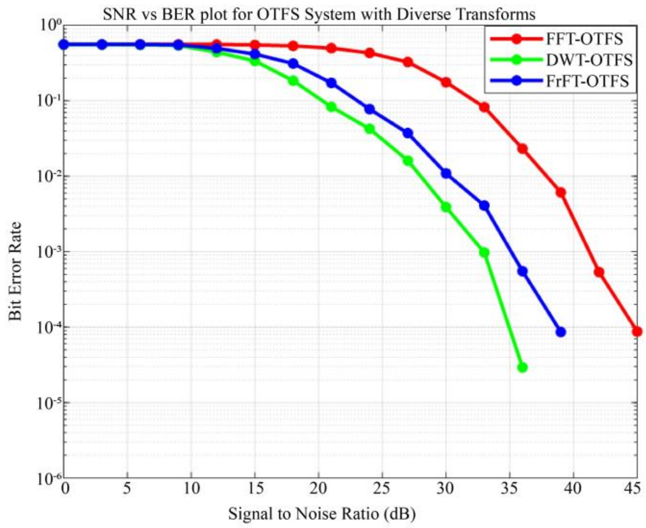
(a)



(b)



(c)



(d)

Fig. 6 (a) - (d): BER vs SNR using various transforms using RICIAN fading at (a) 32PSK, (b) 64PSK, (c) 128PSK, and (d) 256PSK.

The obtained results for the system operated under the Rician fading environment have also been depicted in Table 4.

Table 4. Minimum SNR values required at BER of 10^{-4} using RICAIN channel

Transform Used	32PSK	64PSK	128PSK	256PSK
FFT	35.7dB	40dB	42dB	45dB
DWT	21dB	29dB	32dB	35dB
FrFT	25.7dB	33dB	36dB	38.5dB

From the results obtained by implanting the OTFS-based system under the Rician fading environment, it was observed that, in this case, the DWT-based system performs the best among all other transforms. The minimum required SNR to maintain an acceptable level of BER showed a gradual increase as the modulation levels were increased. The minimum required SNR showed a significant improvement in the case of DWT-based systems compared to conventional FFT and FrFT-based systems. The minimum SNR was seen for a DWT-based OTFS system run at 32 Levels of PSK modulation as 21db, and the highest SNR was seen for an FFT-based OTFS system with 256 levels of modulation as 45db. By comparing the results obtained across different fading channels, it can also be observed that out of all the fading channels, the AWGN-based system shows significant improvement in performance, followed by NAKAGAMI and then RICIAN channels.

12. Conclusion and Future Scope

In this paper, an OTFS system was implemented using DWT, FrFT, and FFT transforms with multiple modulation levels. The system was operated under AWGN, NAKAGAMI, and RICIAN fading environments. A detailed performance evaluation was conducted, and from the simulated results, it was observed that the DWT-based OTFS system outperformed the FrFT and FFT-based OTFS systems. The simulation results also showed that the system yielded its best performance when operated under an AWGN environment and its worst performance when operated under a Rician fading environment. The minimum SNR required to obtain BER of 10^{-4} was found to be as 9db in the case of DWT-based OTFS system under AWGN fading, while the highest SNR found was in the case of FFT-based OTFS system under RICIAN fading as 45db. In the future, the transforms can be extended to MIMO-based OTFS systems and Massive MIMO-based OTFS systems to explore possibilities for further improvement in their performance evaluation parameters.

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