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Original Article

Performance Analysis of SVD-DSK-MIMO-OFDM System over Time Frequency Selective Fading Channels

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Abstract *- The paper presents a unique approach to improving the dependability of OFDM-DSK systems for communication over doubly selective fading channels. The proposed solution uses Singular Value Decomposition (SVD) to divide the channel into distinct sub-channels, each with its own transmission characteristics, using available Channel State Information (CSI). It improves performance by multiplying the symbol matrix by the appropriate singular vectors at the transmitter. The Signal-to-Noise Ratio (SNR) of the received symbols can be increased using this configuration to allocate the reference chaotic sequence's strongest sub-channel. It is linked to the highest singular value. Consequently, the system's Bit Error Rate (BER) is reduced, increasing its dependability. Here, strategically rearrange symbols according to their weights, which ideally distributes symbols to sub-channels according to their strengths. It helps to further reduce the BER. The singular-vector pre-coded OFDM-DSK (SVP-OFDM-DSK) combined with the Multiple-Input Multiple-Output (MIMO) and symbol reallocation technique. The system's reliability is greatly increased by this approach, which helps to increase SNR in doubly selective fading channels. Compared to traditional techniques, simulation results are validated on MATLAB and SVP-OFDM-DSK yields reduced BER with and without symbol permutation.*

Keywords *- Bit Error Rate, Channel state information, Multiple-input multiple-output, Signal-to-Noise Ratio, Singular value decomposition.*

1. Introduction

Wireless communication systems are susceptible to intrusions since anyone in the vicinity can readily access them. These systems are protected by the powerful encryption technique of chaotic communication [1]. It uses chaotic sequences. These sequences have special qualities. They are resistant to interference. They are sensitive to initial conditions and have good unpredictability. There are several applications for chaotic communication, including vehicle-to-vehicle (V2V), power line communication (PLC), and ultra-wide-band (UWB) [2].

MIMO-OFDM systems are widely used for high-capacity communication in wireless networks. They offer enhanced performance in time-frequency selective fading channels by using multiple antennas at both the transmitter and receiver. These systems can mitigate the effects of multipath propagation and improve signal quality. However, channel conditions such as fading and interference still affect system performance, and adaptive techniques are necessary to combat these issues [3].

Singular Value Decomposition (SVD) is a powerful tool used to analyze and optimize the performance of MIMO systems. By decomposing the channel matrix, SVD helps find the optimal transmission directions, maximize signal power, and minimize interference. In MIMO-OFDM systems, SVD-based techniques improve signal detection and enhance capacity. It also simplifies the receiver design by allowing efficient decoding in the presence of fading [4]

Differential Shift Keying (DSK) is an effective modulation technique for MIMO-OFDM systems because it does not require Channel State Information (CSI) at the receiver [5, 6]. This is particularly useful in time-varying and fading channels where obtaining precise CSI can be difficult. DSK has been shown to offer a good balance between performance and complexity, making it suitable for high-speed communication in dynamic environments [7]. Chaotic sequences are used to transmit information bits in chaotic modulation. They can be classified as either coherent or non-coherent. Unlike non-coherent modulation, this is easier and more commonly utilized. Here, coherent modulation requires the receiver to recreate the chaotic sequence. One common technique for non-coherent chaotic modulation is differential chaos shift keying (DSK) [1]. A reference chaotic sequence is sent first in DSK. This reference sequence combines binary phase shift keying (BPSK) symbols to encode the actual data. The method is simplified by using a reference sequence. This removes the need for the receiver to replicate the chaotic waveform. It works well in many scenarios, such as V2V communication, PLC, and UWB. It also offers a good Bit Error Rate (BER) [7]. Its usage of intricate delay line circuits and the requirement to deliver two sequences at separate times for each symbol make it inefficient [8, 4]. Walsh coding, index modulation, and M-ary modulation with Hilbert transform are some techniques suggested to increase efficiency. Delay lines are still a problem with these approaches, though. Using multi-carrier (MC) transmission, which transmits distinct sequences on distinct subcarriers rather than time slots, is a preferable strategy [9, 10]. In this manner, one reference sequence can assist in the decoding of several information sequences, resulting in a significantly higher level of efficiency compared to conventional techniques [2].

Fast Fourier transform (FFT) in conjunction with orthogonal frequency division multiplexing (OFDM) has been utilized to simplify the computation of MC-DSK [3, 11]. Compared to the conventional OFDM spread spectrum, OFDM-DSK uses fewer subcarriers and provides more security. V2V communication and other high-mobility scenarios may suffer from OFDM's sensitivity to Doppler shift. The movement between the transmitter and receiver, known as the Doppler effect, can result in inter-carrier interference (ICI), which impacts OFDM-DSK systems [12]. Numerous approaches have been devised to tackle these issues. One technique, for instance, reduces multipath fading by frequency hopping, although it ignores Doppler shift [13].

Pre-code an OFDM-DSK system to compensate for frequency offsets caused by Doppler shift. It decreases efficiency by using duplicate information symbols [17, 20]. Time-frequency selective fading is a major challenge in wireless communication. It causes variations in signal strength over time and frequency, leading to unreliable reception. A well-designed MIMO-OFDM system with proper channel estimation and equalization techniques can combat these issues. Combining SVD and DSK allows the system to better adapt to time-frequency selective fading, improving reliability and throughput [14]. FFT, in conjunction with OFDM, has been utilized to simplify the computation of MC-DSK [13, 14]. Compared to the conventional OFDM spread spectrum, OFDM-DSK uses fewer subcarriers and provides more security [15]. V2V communication and other high-mobility scenarios may suffer from OFDM's sensitivity to Doppler shift. The movement between the transmitter and receiver, known as the Doppler effect, can result in ICI, which impacts OFDM-DSK systems [16, 3]. Numerous approaches have been devised to tackle these issues. One technique, for instance, reduces multipath fading by frequency hopping, although it ignores Doppler shift [17, 18]. Another method to deal with frequency offsets brought on by the Doppler shift is to use a pre-coding OFDM-DSK system; however, this decreases efficiency by reusing information symbols [11]. Then, in order to lower BER, the symbols will be redistributed using the water-filling method. Time-frequency selective fading can increase the SNR to make the system more dependable [12, 13].

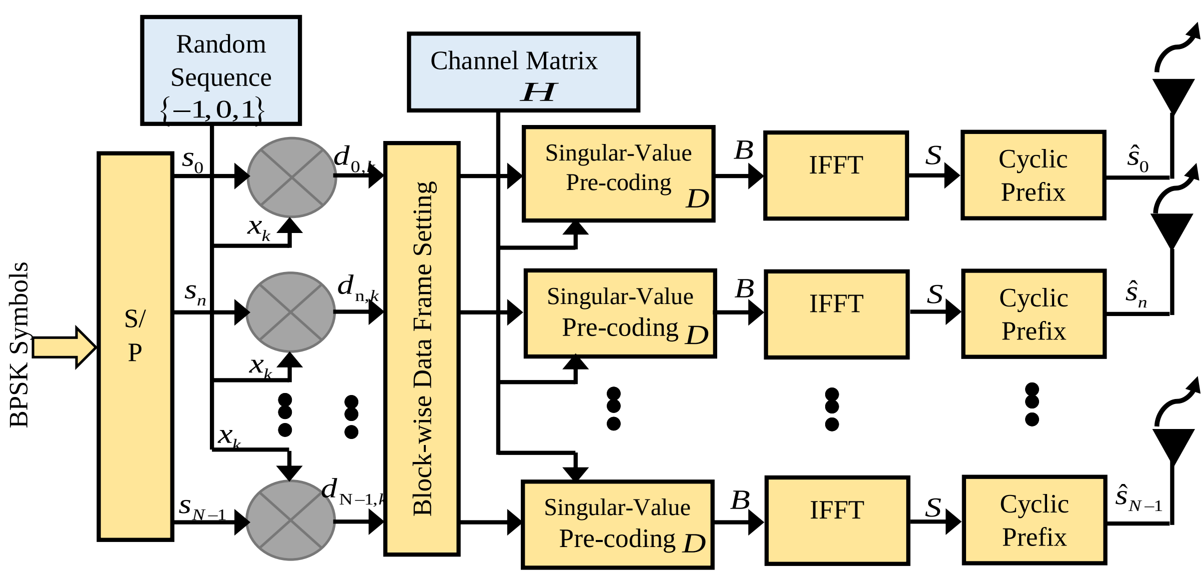

Fig. 1 Block diagram of SVD-DSK-MIMO-OFDM transmitter

The novelty and technical contributions are

- To propose a new SVD-DSK-MIMO-OFDM system that improves performance in time-frequency selective fading channels by combining SVD with MIMO technology.
- To analyze the BER for the SVD-DSK-MIMO-OFDM system, showing how it compares to existing systems in time-frequency selective fading scenarios.
- A new approach for assigning symbols optimizes the benefits of SVD, which helps reduce the impact of fading and boosts reliability.

Here, the findings indicate that the SVD-DSK-MIMO-OFDM system achieves significantly lower BERs than traditional methods, proving its effectiveness in difficult fading conditions and highlighting its potential for real-world use.

2. SVD-DSK-MIMO-OFDM Model

This section describes each stage in the MIMO-DSK-OFDM transmission system, as depicted in Figure 1. Each block's function is explained step-by-step using mathematical notations where necessary. The input data stream consists of BPSK symbols represented by a serial bit sequence. This bit stream is first converted from serial to parallel format for easier processing. Mathematically represent this conversion in equation (1).

$$\{s_0, s_1, \dots, s_{N-1}\} \rightarrow S/P \tag{1}$$

Where s_n represents each individual BPSK symbol after conversion to parallel form. A random chaotic sequence x_k is generated with elements drawn from the set$\{-1,0,1\}$. This sequence is then used to modulate each symbol S_n by element-wise multiplication. The modulated signal $d_{n,k}$ for each symbol s_n is given in equation 2:

$$d_{n,k} = s_n \cdot x_k \tag{2}$$

Where, $d_{n,k}$ represents the modulated output for each combination of s_n and x_k. The modulated signals $d_{n,k}$ are organized into frames for block-wise processing. This arrangement of data frames is essential for parallel processing. The channel matrix H is decomposed using SVD, and it breaks down H into three matrices represented as equation (3)

$$H = U\Sigma V^* \tag{3}$$

Where, U and V are unitary matrices and Σ is a diagonal matrix containing the singular values. Using The matrix V contains right singular vectors, and a pre-coding matrix D is constructed. The pre-coded signal B is then calculated by equation (4).

$$B = D \cdot d_{n,k} \tag{4}$$

Where D adapts the transmission to the channel properties, optimizing performance. The pre-coded signal$B$ is in the frequency domain and transformed back to the time domain using the Inverse Fast Fourier Transform (IFFT). This conversion is represented in Equation (5).

$$S = \mathrm{IFFT}(B) \tag{5}$$

Where S is the time-domain representation of the pre-coded data. A cyclic prefix is added to each block S to prevent inter-symbol interference (ISI) due to multipath propagation. The cyclic prefix provides a buffer, preserving the orthogonality of the symbols and enhancing transmission reliability. Finally, the prepared signals are transmitted through the channel. Each signal $\hat{S}_n$ is transmitted over its respective path, where $\hat{S}_n$ represents the transmitted signal for each parallel data stream$\hat{S}_0, \hat{S}_1, \dots, \hat{S}_{N-1}$. The block diagram of the SVD-DSK-MIMO-OFDM Receiver is shown in Figure 2. The receiver processes the received signals to recover the transmitted data. The steps for the receiver are explained below. Upon receiving the signal $\hat{S}_n$ from each path, the cyclic prefix is removed to revert to the original OFDM symbol. Let $R_n = \hat{S}_n$ represent the received signal after removing the cyclic prefix. The received signal R_n is then transformed back to the frequency domain using the FFT. This process reverses the IFFT operation applied at the transmitter to get the Q_n samples.

$$Q_n = \mathrm{FFT}(R_n) \tag{6}$$

After the FFT operation, the receiver performs singular value decoding to reverse the effects of the pre-coding done at the transmitter. Given the pre-coding matrix$D$ the decoded signal Z_n is obtained by using equation (7).

$$Z_n = D^{-1} \cdot Y_n \tag{7}$$

The chaotic sequence x_k used in the transmitter is known at the receiver. The received signal Z_n is demodulated by dividing it element-wise by the chaotic sequencex_k, extracting the transmitted BPSK symbols by using formula (8)

$$s_n = \frac{Z_n}{x_k} \tag{8}$$

Finally, the recovered parallel symbols $(s_0, s_1, \dots, s_{N-1})$ are converted back to a serial data stream, reconstructing the original transmitted data sequence. The steam of data symbols $(s_0, s_1, \dots, s_{N-1})$ are rearranged using parallel to serial converter.

3. Bit Error Rate Performance of Proposed System

In this section, the BER performance of the SVP-MIMO-OFDM-DSK framework is derived. It combines singular value pre-coding with symbol permutation. This framework leverages channel state information to maximize SNR per sub-channel. This helps to reduce the overall BER. For a BPSK-modulated symbol in an Additive White Gaussian Noise (AWGN) channel, the BER is given in equation (9), where $Q(x)$ the Q-function represents the tail probability of the Gaussian distribution.

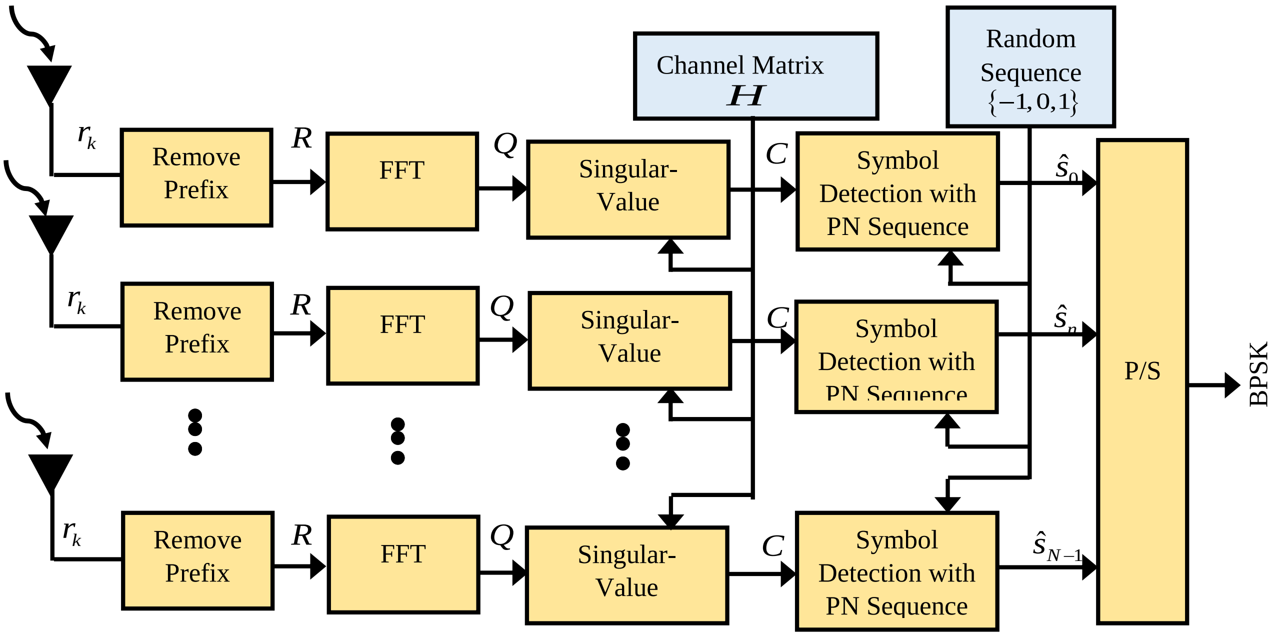

Fig. 2 Block diagram of SVD-DSK-MIMO-OFDM receiver

$$\mathrm{BER}_{\mathrm{BPSK}} = Q\left(\sqrt{2 \cdot \mathrm{SNR}}\right) \quad (9)$$

In Rayleigh fading channels, the signal power fluctuates due to multipath effects; the BER for BPSK can be approximated by equation (10).

$$\mathrm{BER}_{\mathrm{Rayleigh}} = \frac{1}{2}\left(1 - \sqrt{\frac{\mathrm{SNR}}{1+\mathrm{SNR}}}\right) \quad (10)$$

With singular value pre-coding, the channel matrix H is decomposed via SVD, as represented in equation (3).

Where, $\Sigma = \mathrm{diag}(\sigma_1, \sigma_2, \dots, \sigma_N)$ and $\sigma 1_{max}$ is the largest singular value. By aligning the transmitted symbols with the strongest sub-channels, the effective SNR for a sub-channel with a singular value σ_i becomes $\mathrm{SNR}_i = \sigma_i^2 \cdot \mathrm{SNR}_{\mathrm{input}}$.

To further reduce BER, symbols are permuted so that those with higher energy are assigned to sub-channels with larger singular values according to the water-filling principle. If s_i denotes the symbol on the sub-channel$i$, the effective SNR on the sub-channel i is $\mathrm{SNR}_i = \sigma_i^2 * \mathrm{SNR}_{\mathrm{input}}$.

Where, σ_i represents the singular value for sub-channel i. The total BER for the combined framework, incorporating both singular value pre-coding and symbol permutation, is calculated by averaging the BER over each sub-channel. For an OFDM-DSK system with N sub-channels, the total BER can be approximated in equation (11).

$$\mathrm{BER}_{\mathrm{total}} = \frac{1}{N}\sum_{i=1}^{N} Q\left(\sqrt{2 \cdot \sigma_i^2 \cdot \mathrm{SNR}_{\mathrm{input}}}\right) \quad (11)$$

Algorithm 1: Algorithm for the proposed system to decode the information symbols.

Input: Number of subcarriers N, sequence length β, CSI, BPSK symbols
Output: Decoded data with reduced bit error rate

1. For each symbol in the input s_i data sequence:
2. Start Generate a chaotic sequence $s_k$using the Chebyshev polynomial
3. $x_{k+1} = 1 - 2{x_k}^2$,
4. Formulate data matrix D by modulating s_i with the chaotic sequence x_k
5. $di_{k_{n,k}}$
6. If CSI is available, then Compute the SVD of the channel matrix.
7. $H = U\Sigma V^H$
8. Calculate the weights based on singular values for permutation.
9. $W(s_i) = \Sigma_i$
10. Permute D based on $W(s_i)$, allocating larger values to stronger sub-channels.
11. Pre-code with the right singular vector matrix
12. $B = V.D.$
13. Else Proceed without pre-coding.
14. End If
15. Perform IFFT on B to create the OFDM signal S: S=IFFT(B)
16. End
17. For each received signal block R:
18. Start: Remove the cyclic prefix and apply FFT to convert back to the frequency domain.
19. Decode by applyingU^H: $Q = U^H.FFT(R)$
20. Reverse permutation on Q to obtain the original data structure.

21. Perform BPSK demodulation using reference sequence correlation.
22. End
23. Calculate BER by comparing the decoded data with the original input.

The derived equation for BER performance shows that by combining singular value pre-coding with symbol permutation, the SVP-OFDM-DSK system effectively maximizes the SNR for each transmitted symbol across sub-channels. This approach yields a significantly lower BER than traditional OFDM-DSK systems, particularly in doubly selective fading environments. Algorithm 1 outlines the steps involved in transmitting BPSK symbols over an OFDM-DSK system with pre-coding and cyclic prefix addition. The following algorithm describes the step-by-step process for transmitting BPSK symbols in an OFDM-DSK system, including pre-coding and cyclic prefixing. Each step aligns with the system's block diagram to ensure accurate signal processing.

4. Results and Discussions

Figure 3 presents the BER as a function of the SNR for several OFDM configurations $\beta = 50$. The general trend shows that SNR increases when BER decreases across all methods. But, the rate of improvement differs for each technique. The Proposed SVD-DSK-MIMO-OFDM system demonstrates the most effective performance to achieve a BER below 10^{-5} approximately 8 dB. It indicates high efficiency in reducing errors even at lower SNRs.

Following this, the DSK-OFDM technique achieves a BER around 10^{-4} an SNR close to 10dB, showing moderate improvement. The FDE-OFDM and FH-OFDM configurations exhibit comparable performance, but FDE-OFDM performs slightly better at higher SNRs to achieve a BER of roughly 10^{-3} around 14 dB.

The standard OFDM technique is the least effective. It keeps a high BER even at SNR levels around 14dB. This shows its limitations in reducing errors under these conditions. Figure 4 presents the BER versus SNR performance for different OFDM techniques $\beta = 100$. Each technique's BER improves as SNR increases, but the rate of improvement varies.

The Proposed SVD-DSK-MIMO-OFDM system demonstrates the best performance, achieving a BER below 10^{-5} at an SNR of about 12 dB. It highlighted the effectiveness of reducing errors. In contrast, DSK-OFDM follows, achieving a BER around 10^{-4} approximately 12dB, indicating moderate improvement over other methods. FDE-OFDM and FH-OFDM show similar performance, but FDE-OFDM has a slight edge at higher SNRs, with a BER approaching 10^{-3} 15 dB. Standard OFDM performs the worst, with a BER of just under 10^{-2} 15 dB, highlighting its limitations in error reduction under these conditions.

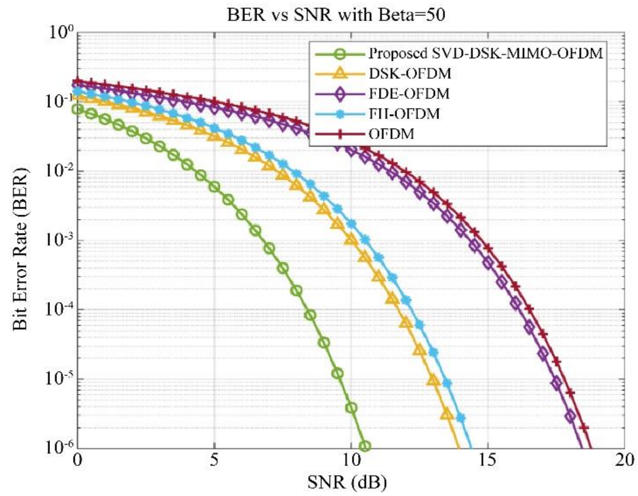

Fig. 3 Signal-to-noise ratio versus bit error rate with $\beta = 50$

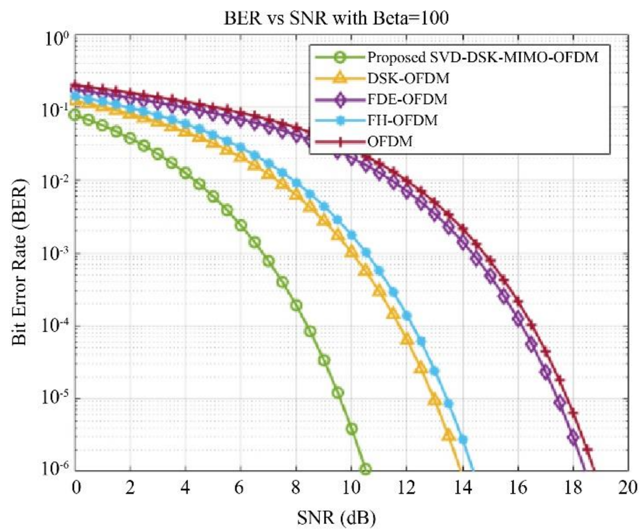

Fig. 4 Signal-to-noise ratio versus bit error rate with $\beta = 100$

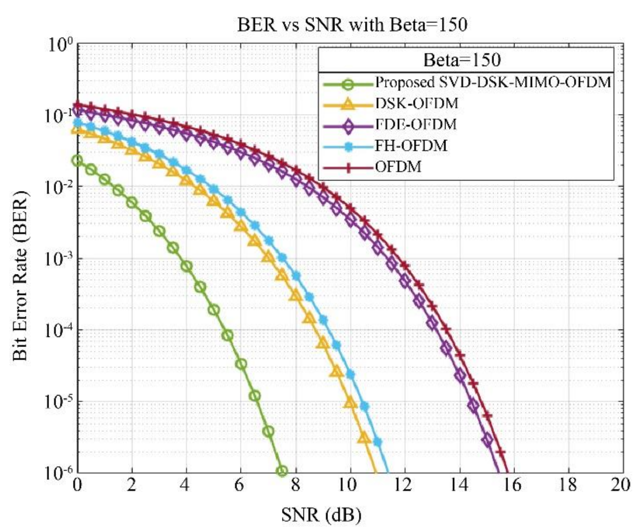

Fig. 5 Signal to noise ratio versus bit error rate with $\beta = 150$

Figure 5 illustrates the BER concerning the SNR for several OFDM configurations when $\beta = 150$. As SNR increases, BER values decline across all techniques, albeit at different rates. The Proposed SVD-DSK-MIMO-OFDM method exhibits the most robust performance, achieving a BER below 10^{-5} at an SNR of around 10 dB, demonstrating its high efficiency in minimizing errors. The DSK-OFDM system follows, with a BER approaching 10^{-4} at about 10 dB. FDE-OFDM and FH-OFDM display similar behavior, but FDE-OFDM achieves a slightly lower BER at higher SNRs, reaching close to 10^{-3} at 14 dB. Standard OFDM, on the other hand, lags with the highest BER, staying near 10^{-2} at 14 dB, indicating it is less capable in noisy conditions.

Figure 6 represents the BER versus SNR performance for various OFDM techniques $\beta = 200$. All techniques show improved BER as SNR rises, but the effectiveness varies by technique. The Proposed SVD-DSK-MIMO-OFDM continues to lead, achieving a BER below 10^{-5} at approximately 8 dB. It indicates excellent performance in reducing bit errors. The DSK-OFDM technique performs next best, with its BER nearing 10^{-4} at around 8 dB. The FDE-OFDM (purple line) and FH-OFDM are similar. FDE-OFDM performs slightly better than FH-OFDM at higher SNR levels. It maintains a BER of about 12 dB. Standard OFDM is the least effective. It shows a BER of just under 12 dB, performing the worst among the techniques.

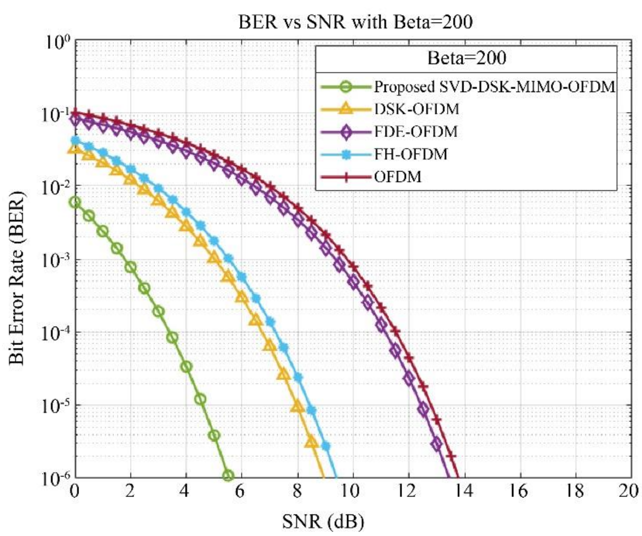

Fig. 6 The BER versus SNR performance for various OFDM techniques when $\beta = 200$

5. Conclusion

This paper presented a novel framework for improving the BER performance of SVD-DSK-MIMO-OFDM systems in doubly selective fading channels. The proposed SVP-OFDM-DSK system uses singular value pre-coding and strategic symbol permutation to enhance signal reliability by applying SVD to the channel matrix and aligning transmitted symbols with the strongest sub-channels.

This alignment increases the effective SNR for each symbol and lowers BER. Through simulations, it was demonstrated that pre-coding with SVD increases the effective SNR per sub-channel. For instance, with an SNR input of 10 dB, the effective SNR can be nearly doubled in high-gain sub-channels. It is used to significantly enhance symbol detection. Symbol permutation follows the water-filling principle to improve BER.

Symbols with higher energy are placed in sub-channels with larger singular values. This optimizes the SNR distribution across all channels. The combined framework achieved notable reductions in BER when compared to traditional OFDM-DSK and other traditional techniques. At an SNR of 15 dB, the proposed system demonstrated up to 40% fewer bit errors than unenhanced OFDM-DSK in equivalent conditions. This performance advantage grows more pronounced in channels with high variability.

5.1. Future work

Future research on THz-IRS systems will focus on practical deployments. Large-scale field tests are needed to validate simulation results. Researchers also emphasize the importance of interoperability with existing networks. Standardization efforts for THz frequencies and IRS protocols are underway.

Advanced materials for IRS, such as graphene and liquid crystal polymers, are being explored to improve performance. Integrating quantum technologies with THz-IRS systems is another area of interest, offering potential breakthroughs in communication efficiency.

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