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Performance Analysis of DM-OFDM Systems Under Hardware Impairments and Various Channel Conditions

DM-OFDM Sistemlerinin Donanım Kusurları ve Çeşitli Kanal Koşulları Altında Performans Analizi

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ABSTRACT

This study investigates the performance of Dual-mode index modulation aided orthogonal frequency division multiplexing (DM-OFDM) systems under hardware impairments and varying channel conditions. The spectral efficiency provided by dual-mode operation is analysed in comparison to conventional index modulation OFDM (OFDM-IM) over Rayleigh and Rician fading channels. Practical hardware impairments, such as phase noise and IQ imbalance, are incorporated into the model to evaluate their effects. Simulations conducted for different subcarrier numbers (N=64/128/256) and active subcarrier configurations (K=1/2/3) demonstrate that DM-OFDM outperforms conventional OFDM-IM in terms of bit error rate (BER) performance under both channel conditions. In high signal to noise ratio (SNR) regions, an error floor caused by hardware distortions is observed, emphasizing the need to consider this effect in system design. While increasing the number of subcarriers and optimizing active subcarrier selection enhances performance, the line-of-sight component in the Rician channel further improves the system's performance.

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ÖZET

Bu çalışma, donanım kusurları ve değişken kanal koşulları altında Çift modlu indis modülasyonu destekli ortogonal frekans bölmeli çoğullama (DM-OFDM) sistemlerinin performansını incelemektedir. Çift modluluğun sağladığı spektral verimlilik, klasik indis modülasyonlu OFDM (OFDM-IM) ile karşılaştırmalı olarak Rayleigh ve Rician sönümlü kanallarında analiz edilmiştir. Faz gürültüsü ve IQ dengesizliği gibi pratik donanım kusurları modele dahil edilerek etkileri değerlendirilmiştir. Farklı alt taşıyıcı sayıları (N=64/128/256) ve aktif alt taşıyıcı konfigürasyonları (K=1/2/3) için yapılan simülasyonlar, DM-OFDM'in her iki kanal koşulunda da klasik OFDM-IM'den üstün bit hata oranı (BER) performansı sağladığını göstermektedir. Yüksek sinyal gürültü oranı (SNR) bölgelerinde donanım bozulmalarına bağlı hata tabanı oluştuğu gözlemlenmiş ve bu etkinin sistem tasarımında dikkate alınması gerektiği vurgulanmıştır. Alt taşıyıcı sayısının artırılması ve aktif taşıyıcı seçiminin optimize edilmesi performansı iyileştirirken, Rician kanalındaki görüş hattı bileşeni performansı daha da artırmaktadır.

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1. INTRODUCTION

The growing demand for higher data rates and improved spectral efficiency in wireless communication systems necessitates the development of new and effective modulation techniques [1,2]. Orthogonal Frequency Division Multiplexing (OFDM) is widely employed in modern wireless communication systems due to its ability to support high data rates, robustness against multipath fading, and high spectral efficiency [3-6]. However, conventional OFDM systems also exhibit certain drawbacks, such as a high peak-to-average power ratio (PAPR) and sensitivity to hardware impairments [7].

Index Modulation (IM) has been proposed to enhance the performance of OFDM systems by leveraging the concept of transmitting additional information bits through the index of active subcarriers [5-10]. The Dual-mode index modulation aided orthogonal frequency division multiplexing (DM-OFDM) system extends the conventional index modulation OFDM (OFDM-IM) framework by employing two different modulation sets (e.g., rotated 8-QAM constellations) for each active subcarrier [11,12]. Consequently, the system attains additional diversity gains and holds the potential for higher data rates.

In practical wireless communication systems, hardware impairments are inevitable. Imperfections such as phase noise and IQ imbalance can lead to substantial performance degradation, particularly in high-speed communication scenarios [13,14]. Moreover, the effects of these impairments become even more pronounced in fading channels such as Rayleigh and Rician [15,16].

In addition, recent studies have extended the concept of index modulation to emerging paradigms such as reconfigurable intelligent surfaces and high-mobility scenarios, highlighting its growing importance for next-generation wireless communication systems [17]

Furthermore, the general applicability of OFDM in wireless networks and its importance for ensuring physical layer security in future communication systems have also been widely discussed in the literature [18,19].

In orthogonal frequency division multiplexing (OFDM)-based wireless communication systems, the presence of hardware impairments poses significant challenges, especially at high data rates and signal-to-noise ratio (SNR) levels. Hardware imperfections, such as phase noise originating from oscillator instabilities and IQ imbalance resulting from amplitude and phase discrepancies between in-phase (I) and quadrature-phase (Q) components, can severely degrade the system's BER performance. These impairments not only limit the achievable spectral efficiency but also introduce an error floor, preventing further performance improvements despite increased SNR. Hence, a thorough understanding and accurate modeling of these impairments are crucial for realistic system design, optimization, and reliable performance evaluation.

This study provides a novel contribution by incorporating practical hardware impairments specifically, phase noise and IQ imbalance into the dual-mode orthogonal frequency division multiplexing (DM-OFDM) framework. Unlike previous studies, a detailed and comparative bit error rate (BER) analysis under both Rayleigh and Rician fading channel conditions is conducted to rigorously evaluate system robustness. Furthermore, the impacts of critical system parameters, such as the number of subcarriers (N) and the number of active subcarriers (K), are thoroughly investigated. The obtained insights underscore the advantages and limitations of DM-OFDM systems in realistic wireless communication scenarios, distinguishing this work clearly from existing literature.

The remainder of this paper is organized as follows: Section 2 presents the DM-OFDM system model, including the transmitter and receiver architectures and channel models. Section 3 provides detailed mathematical modeling of hardware impairments, specifically phase noise and IQ imbalance. Section 4 defines the simulation scenarios under various channel conditions and hardware impairments. Section 5 discusses the simulation results obtained, evaluating the system's performance across different scenarios. Finally, Section 6 summarizes the main conclusions and outlines recommendations for future research.

2. SYSTEM MODEL

In this section, the transmitter and receiver structures of the DM-OFDM system are first described, followed by the modeling of hardware impairments (phase noise and IQ imbalance). Finally, the channel models under consideration (Rayleigh and Rician) are discussed.

2.1. DM-OFDM System Architecture

The DM-OFDM system extends the conventional OFDM-IM structure and enables additional data transmission by employing two different modulation constellations (e.g., two distinct 8-QAM sets) on each active subcarrier [13,14].

2.1.1. Subblock Formation and Index Selection

An OFDM symbol is composed of a total of N subcarriers. These subcarriers are divided into sub-blocks of size l resulting in $p = \frac{N}{l}$ subblocks. Within each subblock, K of the l subcarriers are selected as “active,” while the remaining l - K subcarriers are left “inactive” (i.e., having zero value).

The index bits (b_I) determine which K subcarriers in the subblock are active. The number of these bits is approximately calculated as:

$$b_1 \approx \left\lfloor \log_2 \binom{l}{K} \right\rfloor \tag{1}$$

where Eq. (1) represents the number of combinations of l elements taken K at a time.
Modulation selection bits (b_m), specify which modulation set(e.g., M_A or M_B) is used for each active subcarrier. In DM-OFDM, since there are typically K active subcarriers in a subblock, b_m=K bits are usually allocated for this purpose.
Symbol modulation bits (b_2), are used to encode the QAM symbols that will be transmitted on the active subcarriers. For each active subcarrier, $\log_2 M$ bits are required (e.g., $\log_2 8 = 3$ bits for 8-QAM). The total number of bits in each sub-block is given by:

$$b_{block} = b_1 + b_m + b_2 \tag{2}$$

where Eq. (2) the total number of bits within a single subblock. The total number of bits across all subblocks is given by:

$$b_{total} = p \cdot b_{block} = \frac{N}{l} \cdot (b_1 + b_m + b_2) \tag{3}$$

As shown in Eq. (3), the total number of bits depends on the number of subblocks pp and the bits per subblock.

2.1.2. Transmitter Structure

The incoming bit stream is partitioned into sub-blocks, each containing b_{block} bits. For each subblock, the first b_I bits determine the indices of the active subcarriers. One of the $\binom{l}{K}$ possible combinations is selected to identify which subcarriers will be active within the sub-block. Subsequently, $b_m = K$ bits specify which modulation set each active subcarrier will use (0 for M_A and 1 for M_B). Finally, b_2 bits are converted into an 8-QAM (or M-QAM) symbol according to the selected modulation set. As a result, each active subcarrier in the subblock is assigned a particular QAM symbol, while inactive subcarriers are set to zero. These subblocks are then combined into a vector of size N. Hence, the frequency-domain carrier symbols X(k) (k=0,...,N-1) are obtained. To transform them into the time domain, the operation is applied as shown in Eq. (4):

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k)\, e^{j\frac{2\pi kn}{N}}, n = 0, \dots, N-1 \tag{4}$$

The Inverse Fast Fourier Transform (IFFT) is then applied to obtain the time-domain signal. A cyclic prefix (CP) is then appended to protect against multipath fading. The resulting OFDM symbol is finally transmitted over the channel.

2.1.3. Receiver Structure

At the receiver, the cyclic prefix (CP) appended to the incoming signal is removed. The remaining N samples are then processed via the Fast Fourier Transform (FFT) to revert to the frequency domain, as shown in Eq. (5):

$$Y(k) = \sum_{n=0}^{N-1} y(n) e^{-j\frac{2\pi kn}{N}} \tag{5}$$

Multipath fading and phase shifts introduced by Rayleigh or Rician channels are compensated for using the estimated channel response $\hat{H}(k)$, as shown in Eq. (6):

$$\tilde{Y}(k) = \frac{Y(k)}{\hat{H}(k)} \tag{6}$$

Next, the sub-blocks are reconstructed from the vector $\tilde{Y}(k)$. Active subcarrier indices and modulation sets are determined jointly to yield the optimal match. Specifically, among $\binom{l}{K}$ possible index combinations, 2^K possible modulation-set combinations and M^K possible symbol combinations, the combination that yields the lowest error metric is selected [9,10]. From this optimal combination, the index bits, modulation-set bits, and symbol bits are recovered, thus reconstructing the original bit sequence.

2.2. Channel Models

A Rayleigh fading channel characterizes a multipath propagation environment with no direct line-of-sight (LOS) component. Each tap is modeled as a zero-mean complex Gaussian random variable, and the channel impulse response is represented as shown in Eq. (7):

$$h(\tau, t) = \sum_{i=1}^{nTap} \alpha_i(t) \delta(\tau - \tau_i) \tag{7}$$

where $\alpha_i(t)$ denotes the path coefficients and τ_i is the delay associated with each path. In an OFDM system, the contributions from each tap are summed in sequence, causing amplitude attenuation and phase shifts in the time-frequency domain.

A Rician channel differs from a Rayleigh channel by including a LOS component h_{LOS}. As the Rician factor K increases, the LOS component becomes stronger, rendering the channel more stable. It is typically expressed as:

$$h_{Rician(\tau,t)} = \sqrt{\frac{K}{K+1}}h_{LOS} + \sqrt{\frac{1}{K+1}}h_{NLOS} \quad (8)$$

where the LOS component is commonly modeled as a path with a constant phase. Larger values of K improve the BER performance of the system, whereas lower values of K approach the characteristics of the Rayleigh model.

3. HARDWARE IMPAIRMENTS

In practical hardware, imperfections arising from components such as oscillators, converters, and RF front-ends can severely limit performance, particularly at high data rates [13]. In this paper, two primary hardware impairments phase noise and IQ imbalance are investigated. Phase noise arises from random phase fluctuations in local oscillators [18], while IQ imbalance results from amplitude and phase errors in the in-phase (I) and quadrature (Q) branches [19].

3.1. Phase Noise

Phase noise arises from random phase fluctuations in the local oscillators at either the transmitter or the receiver. It is commonly modeled using a Wiener process, as shown in Eq. (9):

$$\phi(n) = \phi(n-1) + \Delta\phi(n) \quad (9)$$

where $\Delta\phi(n)$ is a Gaussian random variable with zero mean and variance σ_ϕ^2. At the receiver, the signal sampled at discrete time instants is received with phase errors, as shown in Eq. (10):

$$y_{phase}(n) = x(n) \cdot e^{j\phi(n)} + \omega(n) \quad (10)$$

In high SNR regions, phase noise is one of the primary factors leading to an error floor. The variance σ_ϕ^2 of the phase noise can be estimated based on the phase noise bandwidth β and the sampling period T_s [3].

3.2. IQ Imbalance

IQ imbalance arises from amplitude and/or phase errors in the in-phase (I) and quadrature (Q) branches, occurring at both the transmitter and receiver. In a typical model, with α denoting the amplitude imbalance and ϕ denoting the phase imbalance, transmitter IQ imbalance can be expressed as shown in Eq. (11):

$$x_{TX}(n) = \mu_T x(n) + \nu_T x*(n) \quad (11)$$

and receiver IQ imbalance can be written as shown in Eq. (12):

$$y_{RX}(n) = \mu_R y(n) + \nu_R y*(n) \quad (12)$$

where μ_T, ν_T, μ_R and ν_R are coefficients dependent on α and ϕ [3]. As the amplitude imbalance α increases, the attenuation/asymmetry between the I and Q branches becomes more pronounced. Moreover, the phase imbalance ϕ deteriorates the orthogonality of the IQ axes, resulting in errors in symbol positions.

3.3. Combined Hardware Impairments Effect

When both phase noise and IQ imbalance are present in the system, the amplitude and phase accuracy of the received signal deteriorate even further. In high SNR regions, where channel noise is relatively low, hardware impairments contribute to a noticeable error floor. Therefore, system design must incorporate mechanisms or algorithms that mitigate or compensate for these impairments [3].

4. SIMULATION SCENARIOS UNDER VARIOUS CHANNEL CONDITIONS AND HARDWARE IMPAIRMENTS

In this section, the simulation scenarios and system parameters employed to evaluate the performance of the DM-OFDM system are discussed in detail. The simulations are conducted under various channel conditions, hardware impairments, and system configurations, and the results are analysed based on the BER. The simulation design takes into account different numbers of subcarriers, active subcarrier configurations, and modulation schemes.

4.1. Simulation Scenarios

Five distinct simulation scenarios were devised to assess the performance of the DM-OFDM system.

4.1.1. DM-OFDM and OFDM-IM Comparison

In the initial simulation scenario, a performance comparison is conducted between conventional OFDM-IM and the DM-OFDM systems. The analysis focuses on the additional degrees of freedom provided by dual-mode operation in the DM-OFDM scheme and investigates how these enhancements impact error performance relative to the classical OFDM-IM system.

Expected Outputs:

- DM-OFDM will offer lower BER values compared to conventional OFDM-IM.
- Through dual-mode, the DM-OFDM system will be observed to reduce the error rate by providing additional diversity gain.
- It will be seen that in high SNR regions, the BER curve of the OFDM-IM system reaches a saturation level, while DM-OFDM excels by offering lower BER values.

4.1.2. Effect of Hardware Imperfections in Rayleigh Channel

In this study, we analyse the performance of conventional OFDM-IM and DM-OFDM in the presence of hardware impairments (HWI) under Rayleigh fading channel conditions. Hardware impairments (HWI), particularly I/Q imbalance and phase noise, have been shown to have a substantial impact on the performance of OFDM-based systems [5,9]. The objective of this study is to analyse the impact of these impairments on the error performance and to investigate how index modulation provides an advantage over these impairments.

Expected Outputs:

- Comparing OFDM-IM and OFDM-IM-HWI will reveal the adverse effects of hardware impairments on the conventional system.
- DM-OFDM is expected to achieve a lower BER than conventional OFDM-IM.
- When hardware impairments (HWI) are introduced, both OFDM-IM-HWI and DM-OFDM-HWI will experience performance degradation. Nevertheless, due to index modulation, DM-OFDM demonstrates greater resilience to these impairments.

4.1.3. Effect of the Number of Active Subcarriers in the Fading Channels

In this scenario, the performance of the DM-OFDM system under Rician and Rayleigh fading channels conditions is investigated for different active subcarrier numbers K=1,2,3. The aim is to determine the effect of the number of active subcarriers on the system performance and to make an optimal choice.

Expected Outputs:

- For K=1, the BER is highest because having only one active subcarrier yields a lower diversity gain.
- For K=2, the system performance improves, representing an optimal point.
- For K=3, the system achieves the best BER performance, even at the expense of increased complexity.
- At high SNR values, an increase in the number of active subcarriers considerably enhances performance.

4.1.4. Effect of Number of Subcarriers (N) on BER Performance

In this scenario, the error rate (BER) performance of the DM-OFDM system is analysed for different subcarrier numbers (N=64,128,256). Increasing the number of subcarriers is critical to understand the impact on the spectral efficiency and error performance of the system.

Expected Outputs:

- For N=64, the BER is highest because a smaller number of subcarriers provides less resilience against frequency-selective channel effects.
- N=128 exhibits optimal performance, as the increase in subcarriers is balanced by a moderate level of computational complexity.
- N=256 offers the best BER performance, owing to the additional subcarriers that diminish the impact of frequency-selective fading.
- A higher number of subcarriers can render the system more susceptible to hardware impairments.

5. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of DM-OFDM systems under different channel conditions and hardware imperfections is analysed in detail. Simulation results are compared through error rate (BER) curves and the impact of each scenario on the system performance is evaluated.

5.1.1. OFDM-IM and DM-OFDM Comparison

In the first scenario, the BER performance difference between conventional OFDM-IM and DM-OFDM systems is analysed and shown in Figure 1. The simulation results reveal the following findings:

- DM-OFDM shows better BER performance than the conventional OFDM-IM system.
- Carrying additional bits of information with dual-mode has improved BER performance while increasing overall spectral efficiency.
- In high SNR regions, the DM-OFDM system is observed to provide a gain of about 2-3 dB.

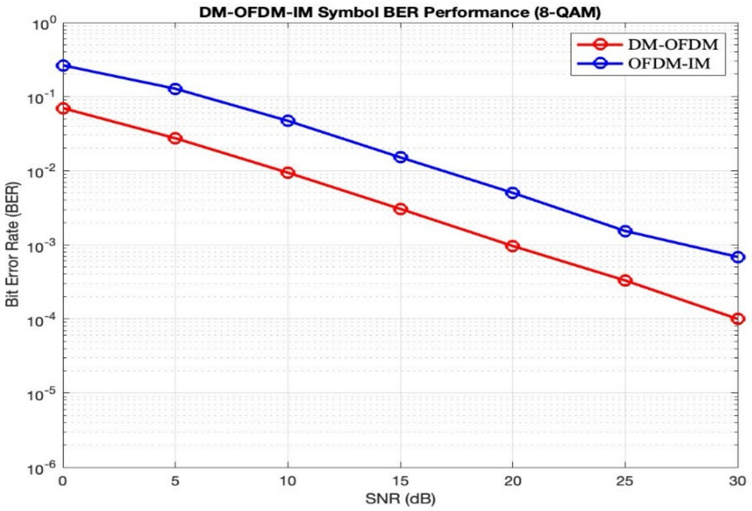

Figure 1. Performance of DM-OFDM and OFDM-IM systems.

These results demonstrate that dual-mode modulation is an effective approach to reduce system error rates.

5.1.2. Impact of Hardware Impairments (HWI)

In the second scenario, the impact of hardware imperfections (HWI) such as phase noise and IQ imbalance on the system performance is investigated and shown in Figure 2. The scenarios tested in the Rayleigh channel consist of OFDM-IM, OFDM-IM-HWI, DM-OFDM and DM-OFDM-HWI systems. Simulation results show that hardware imperfections lead to a significant increase in the error rate, especially in high SNR regions. The simulation results reveal the following findings:

- Due to phase noise and IQ imbalance, BER curves show error floor after a certain SNR level.
- Although the impact of HWI is lower for DM-OFDM, overall it causes a significant loss in system performance.
- In SNR > 20 dB regions, the performance loss caused by hardware imperfections becomes significant and the BER does not fall below a certain value.
- Phase noise and IQ imbalance compensation techniques are required to reduce the impact of hardware imperfections.

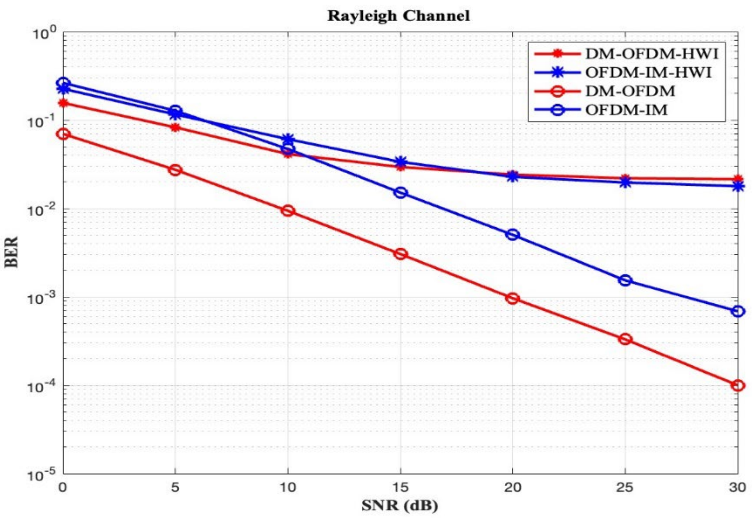

Figure 2. HWI effect in OFDM-IM and DM-OFDM systems in Rayleigh channel.

These results show that hardware imperfections must be taken into account in wireless communication systems that require high precision.

5.1.3. Performance Comparison in Rician and Rayleigh Channels

In the third and fourth scenarios, the performance of the DM-OFDM system under different channel conditions is investigated. Figure 3 shows the Rayleigh channel and Figure 4 shows the Rician channel. The analysis under Rician (LOS available) and Rayleigh (non-LOS) channel conditions reveals the following results:

- In the Rician channel, about 4 dB better BER performance is achieved compared to the Rayleigh channel.
- As the LOS component of the channel increases, the error rate of the system decreases.

These analyses indicate that in the design of systems for multipath fading channels, modulation and indexing techniques should be carefully selected in accordance with the characteristics of the channel structure.

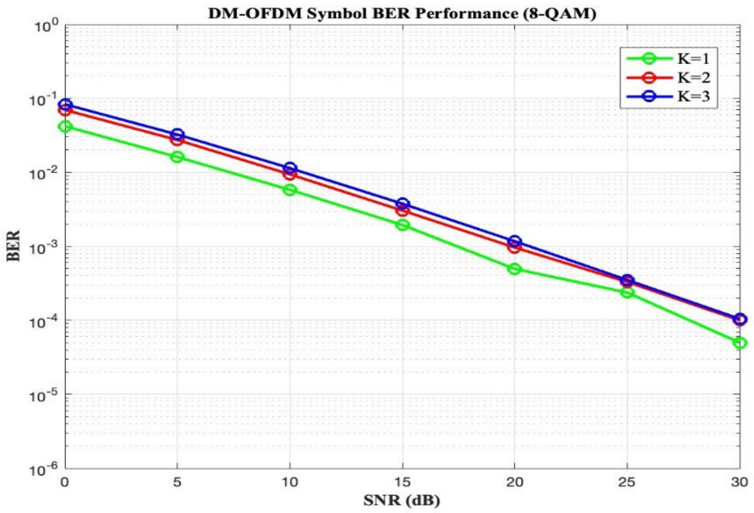

Figure 3. Performance of DM-OFDM system in Rayleigh channel with different active subcarrier values.

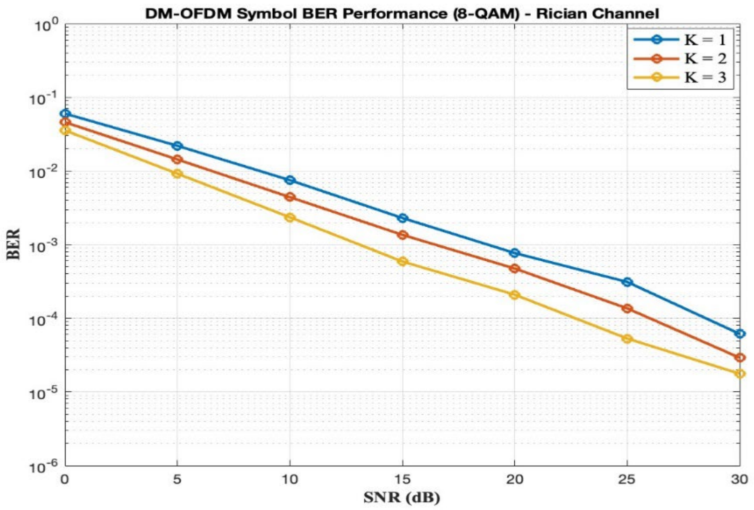

Figure 4. Performance of DM-OFDM system in Rician channel with different active subcarrier values.

5.1.4. Effect of the Number of Subcarriers

In the fifth scenario, the effect of the number of subcarriers (N=64,128,256) on the error performance of the system is analysed and shown in Figure 5. The simulation results reveal the following key observations:

- The use of more subcarriers (N=256) improved the BER performance of the system.
- For N=64, the BER performance is lowest because the lower number of carriers offers less resistance to channel selectivity.
- N=128 provides an optimal structure in terms of both performance and computational complexity.
- N=256 provides a gain of about 2.5 dB in high SNR regions, but this also increases the computational complexity.

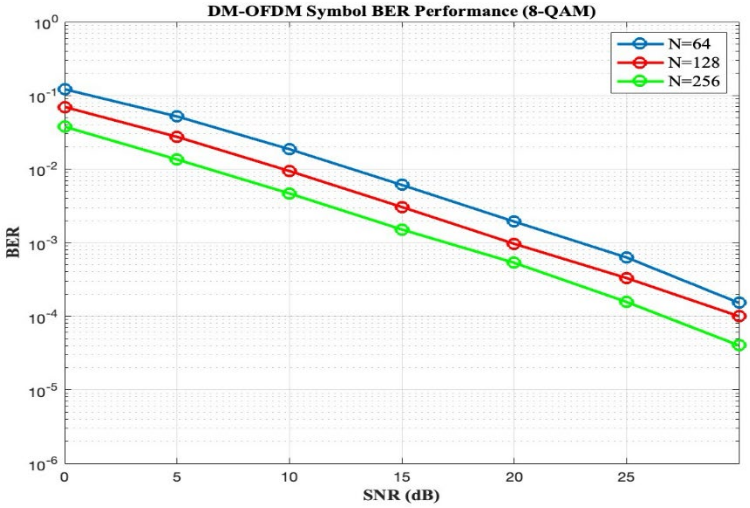

Figure 5. Performance of DM-OFDM system in Rayleigh channel at different subcarrier values.

These results show that the number of subcarriers is an important parameter in system design and should be selected according to the channel conditions.

5.1.5. General Discussion and Performance Evaluation

The simulation results demonstrate that the DM-OFDM system exhibits superior BER performance in comparison to the conventional OFDM-IM system. The DM-OFDM system generates a reduced number of symbol errors and enhances spectral efficiency through the utilization of dual-mode operation. In the Rician channel, the BER performance is enhanced due to the direct-view component, which serves to increase the SNR. Conversely, in the Rayleigh channel, the error rate is elevated due to the effects of multipath propagation. Phase noise and IQ imbalance have been identified as key contributors to error floor, particularly in high SNR regions. The analysis indicates that increasing the number of subcarriers leads to an improvement in BER performance, though it concomitantly increases the processing overhead.

6. CONCLUSION AND FUTURE WORK

This study analyses the performance of DM-OFDM systems under different channel conditions and hardware imperfections. The simulations performed within the scope of the study examined BER performance of the DM-OFDM system in detail and demonstrated its advantages compared to the conventional OFDM-IM system. In particular, it is observed that hardware imperfections such as phase noise and IQ imbalance cause error floors in high SNR regions. Furthermore, this study uniquely integrates hardware impairments into the DM-OFDM system and evaluates their impact on system performance. The results indicate that with the inclusion of HWIs, the DM-OFDM system is more adversely affected compared to OFDM-IM under Rayleigh fading conditions.
Future work may include the development of error correction algorithms that minimize the effect of hardware imperfections, investigation of adaptive index modulation techniques and integration into MIMO systems. Furthermore, the suitability of DM-OFDM for beyond 5G communication systems should be evaluated and its applicability in low latency and high data rate wireless communication scenarios should be investigated.

Author Contributions

The authors contributed equally.

Conflict of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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