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Performance evaluation of multicarrier quadrature phase shift keying-based system under noisy channel conditions

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ABSTRACT

A comprehensive analysis of quadrature phase shift keying (QPSK) modulation in both single input single output (SISO) and multiple input multiple output (MIMO) systems is conducted using MATLAB. The investigation focuses on evaluating QPSK performance with metrics such as signal-to-noise ratio (SNR) and bit error rate (BER) across diverse channel conditions. Furthermore, the study extends to encompass the integration of QPSK with orthogonal frequency division multiplexing (OFDM), with a particular emphasis on assessing spectral efficiency and error rate implications. To validate the accuracy of the simulations, QPSK and QPSK-OFDM configurations are implemented on the WiComm-T hardware platform, enabling a direct comparison of real-world performance metrics against simulation results. By offering practical insights and recommendations for the deployment of robust communication systems, this research underscores the inherent advantages of integrating OFDM with QPSK across both SISO and MIMO configurations.

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1. INTRODUCTION

In modern wireless communication systems, modulation techniques play a pivotal role in determining the efficiency and reliability of the system. Quadrature phase shift keying (QPSK) is known for its ability to encode data by shifting the phase of a carrier signal to one of four distinct states, allowing two bits per symbol to be transmitted. Extending the analysis, the scope also includes orthogonal frequency division multiplexing (OFDM) combined with QPSK within the multiple-input and multiple-output (MIMO) framework. OFDM, a method that divides a high-data-rate signal into multiple lower-data-rate signals transmitted simultaneously over different subcarriers. The study of the modulation schemes is mostly simulation-based. However, these simulations often fail to capture the full complexity of real-world communication environments. This creates a potential mismatch between theoretical predictions and actual system behavior. This study focuses on validating the simulation results of QPSK and QPSK-OFDM configurations using the WiComm-T hardware platform. Evaluating the impact of signal-to-noise ratio (SNR) on bit error rate (BER) performance across these modulation schemes is a critical aspect of this study. By conducting comprehensive simulations and analyzing BER versus SNR, detailed insights are provided into the efficiency and reliability of QPSK and OFDM-based modulation techniques in modern wireless communication systems. The goal is to highlight the advantages and trade-offs associated with each configuration, examining how each performs under varying conditions and SNR levels, and how they can be optimized to enhance communication system performance. This in-depth analysis will contribute to a better understanding of the practical applications and limitations of these modulation techniques, which are critical for the development and improvement of contemporary and future wireless communication systems. The integration of QPSK with OFDM in a MIMO framework is particularly significant, as it provides the benefits of efficient phase-shift keying with OFDM. This comprehensive examination underscores the pivotal role of sophisticated modulation techniques in meeting the escalating demands for data in an increasingly connected world, thereby fostering continued innovation and advancement in the field of wireless communications.

Several studies have contributed to the development of QPSK modulation in different contexts. A novel QPSK modulation architecture based on time-mode signal processing, which enhances energy efficiency, is investigated in [1]. Chowdhury *et al*. [2] proposed an improved QPSK modulation technique tailored for wireless communication, addressing performance enhancements in noisy environments. The performance of coded OFDM using 4QPSK and 16 quadrature amplitude modulation (QAM), providing insights into BER performance under varying conditions, is discussed in [3]. The QPSK modulation scheme was assessed using theoretical and practical implementations in [4], [5]. Various modulation schemes in digital communication, emphasizing their role in enhancing spectral efficiency, are discussed in [6], [7], with emphasis on the interplay between modulation and coding techniques. MATLAB and Simulink environments were used to evaluate symbol error rates (SER) in different modulation systems. This work focused on developing applications for modulation techniques, alongside the practical and theoretical error rates of different modulation schemes were compared and analyzed. A novel 32-point modulation scheme aimed at improving spectral utilization and signal efficiency is discussed in [8]. As an alternative to the four-dimensional modulation scheme, hybrid modulation techniques are proposed to enhance the spectral utilization. The QPSK performance in multipath fading channels is studied in [9], [10], necessitating additional equalization techniques in highly dispersive fading channels. A mathematical analysis in the form of closed-form expressions for the bit error probability performance of different signal constellations is also derived.

The contemporary algorithms and research perspectives with a deeper insight into MIMO-OFDM systems are discussed in [11], [12]. The authors have conducted extensive reviews and performance evaluations of MIMO-OFDM techniques using analytical and simulation-based approaches. The advanced MIMO-OFDM implementations demanded sophisticated hardware, increasing costs and limiting accessibility. An adaptive minimum bit error rate (MBER) beamforming technique for QPSK receivers is investigated in [13]–[15], focusing on direct BER minimization. Their results show improved performance in interference-prone wireless environments, especially under multipath fading. The authors in [16], [17] have investigated beamforming techniques for mmWave communication, highlighting the importance of beam alignment to enhance signal reliability and improve spectral efficiency. Barb *et al.* [18] employed simulations to assess beamforming techniques in QPSK communication. The results demonstrated that adaptive MBER beamforming enhances QPSK receiver performance, reducing BER significantly. A comprehensive view of 5G beamforming with the advantages of hybrid beamforming in 5G networks is highlighted in [19]–[21]. The BER is evaluated using simulations in an MIMO-OFDM framework using various modulation schemes under fading scenarios in [22], [23]. A possible testbed implementation of the MIMO framework is done in [24] using universal software radio peripheral (USRP) boards. A beam index modulation (BIM) design is discussed in [25] to improve spectral efficiency in wireless systems. The error performance for PSK and QAM in non-ideal OFDM systems is investigated in [26], revealing the degradation in BER under realistic channel conditions.

Each of these papers provides valuable insights into QPSK modulation, beamforming, and MIMO systems, particularly within the context of 5G wireless communication. The existing work in beamforming and QPSK modulation is primarily simulation-based, and there is a notable gap in hardware implementation. The lack of hardware-based verification raises concerns about the practical applicability and reliability of the simulation outcomes, as they do not fully capture the environmental and implementation constraints of a communication system. While the previous studies did not explicitly investigate the hardware implementation, this work aims to bridge the gap by validating the accuracy of the simulation studies in [20] for QPSK and QPSK-OFDM configurations with the WiComm-T hardware platform, enabling a direct comparison of real-world performance metrics against simulation results. A summary on the major contributions of this paper is given as follow:

i) Implementing the QPSK and QPSK-OFDM configurations in a simulation environment using similar using MATLAB [22].
ii) Deploying the same configurations on the WiComm-T platform to capture real-time performance data.
iii) Measuring key performance indicators such as BER, SNR from both simulation and hardware-based experiments.

iv) Performing a detailed comparison between the simulation and hardware results to validate the accuracy of the simulations.

2. METHOD

The performance of an OFDM system combined with QPSK modulation for both single input single output (SISO) and MIMO configurations is carried out using MATLAB. Additionally, beamforming techniques are incorporated to enhance system performance. In this work, MATLAB is utilized to simulate the integration of OFDM and QPSK scheme, process the data, and generate graphs illustrating the relationship between SNR and BER. Its built-in functions and toolboxes make it an ideal choice for tasks such as signal processing and data analysis, essential for evaluating the system's performance. These visualizations help assess the effectiveness and reliability of the modulation scheme under various noise conditions, providing a comprehensive comparison between SISO and MIMO performance.

2.1. Integration of orthogonal frequency division multiplexing and quadrature phase shift keying

Combining OFDM with QPSK leverages the strengths of both technologies, leading to enhanced performance in wireless communication systems. The integration of OFDM and QPSK enhances data transmission, particularly in environments with high interference and significant multipath effects. For instance, in urban areas filled with numerous obstacles that cause signal reflections, OFDM effectively manages the multipath propagation by dividing the high-data-rate signal into multiple lower-data-rate signals, each transmitted simultaneously over different orthogonal subcarriers. This orthogonality prevents inter-carrier interference and optimizes the use of available bandwidth. The block diagram of OFDM transmitter and receiver system is shown in Figure 1. QPSK ensures that the data is transmitted efficiently and accurately by encoding information in phase shifts, allowing for robust communication even in noisy environments.

Two WiComm modules facilitated communication between devices through interconnections. As shown in Figure 2, in the initial setup, these modules were configured and initialized in MATLAB to establish a communication channel. Each device had a transmitter and receiver. After initialization, one device transmitted a signal, while the other captured packets for analysis. The analysis indicated a successful capture of 50,000 packets without any instances of packet loss.

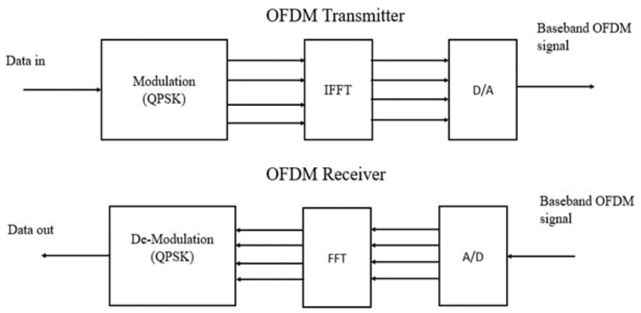

Figure 1. OFDM transmitter and receiver

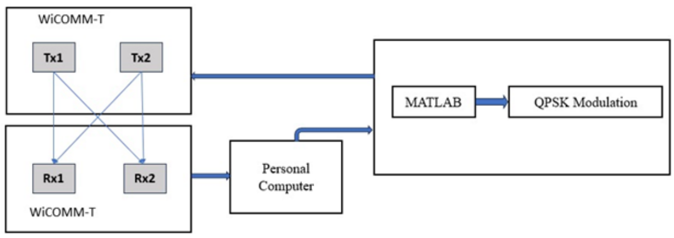

Figure 2. Block diagram

2.2. Performance evaluation

The performance of the OFDM system combined with QPSK modulation for both SISO and MIMO configurations is measured using the following metrics: SNR: in the context of digital communication, SNR is often related to the energy-per-bit to noise power spectral density ratio. E_b is the energy per bit expressed in Joules per bit, and N_0 is the noise power spectral density in W/Hz. A higher SNR indicates a stronger signal, facilitating better reception and reducing the likelihood of errors during transmission.

$$SNR = 10^{\frac{\frac{E_b}{N_0}}{10}} \tag{1}$$

Channel capacity: this parameter represents the maximum rate at which information can be transmitted reliably over a communication channel. It provides insights into the channel's bandwidth and noise characteristics. The aids optimizing communication systems for efficient and performance in (2).

$$C = B \times log_2(1 + SNR) \tag{2}$$

QPSK modulation: to create a QPSK waveform, denoted as $s_{QPSK}(t)$ that is orthogonal and suitable for transmission, we employ amplitude modulation on the in-phase and quadrature data streams using the cosine and sine functions of a carrier wave. The input data is primarily divided into two parallel bit stream components. The in-phase stream $d_I(t)$ is modulated with the cosine waveform and the quadrature stream $d_Q(t)$ is modulated with the sine waveform. The sine and the cosine terms are orthogonal and hence do not interfere with each other. This modulation is achieved in (3).

$$s_{QPSK}(t) = \frac{1}{2}d_I(t).\cos\left(2\pi ft + \frac{\pi}{4}\right) + \frac{1}{2}d_Q(t).\sin\left(2\pi ft + \frac{\pi}{4}\right) \tag{3}$$

3. FLOW OF PROCESS

The workflow involved in the experimental setup using the WiComm-T device, which includes installation of the necessary drivers and interfaces in the transmission and reception of QPSK-modulated signals, is detailed in Figure 3. The key metrics aimed to be analyzed are SNR and BER. The constellation diagram and error graphs are visualized to assess system performance.

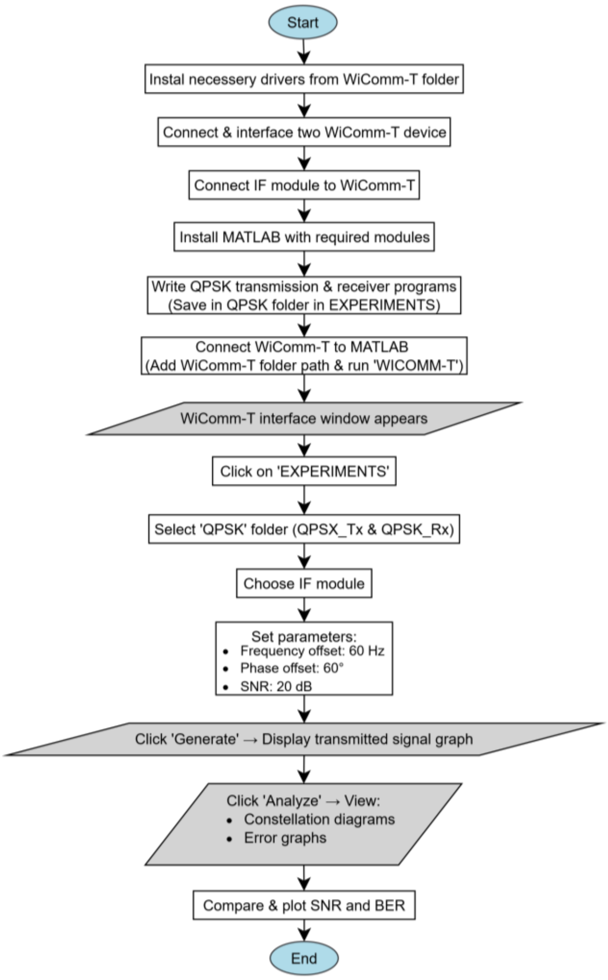

Figure 3. Workflow for QPSK transmission and reception using WiComm-T in MATLAB

4. RESULTS AND DISCUSSION

The WiComm-T device setup is shown in Figure 4 for transmitting and receiving packets. The input configuration given to WiComm-T is given in Table 1. After successfully transmitting and receiving around 50,000 packets, which is essential for ensuring proper transmission, the system's performance and obtain the corresponding output responses is analyzed. In this particular instance, the transmission of approximately 55,236 packets and received the same number of packets with no packet loss. This flawless transmission process can also be observed directly on the kit, where the transmission (TX) and reception (RX) indicators blink, signifying clear and efficient packet transmission. Once the packets are transmitted, a graph that displays the data is observed. The graph typically represents QPSK data, with the magnitude plotted on both the x- and y-axis. This visualization helps in assessing the integrity and quality of the transmitted data, confirming that the system is performing optimally without any loss or degradation of packets during the transmission process.

4.1. Quadrature phase shift keying

Figure 5 illustrates a scatter plot of received symbols post-QPSK demodulation using WiComm-T, where each point represents a symbol carrying two bits of information, determined by its in-phase (I) and quadrature (Q) components. Ideally, a QPSK constellation forms a square with four points, each positioned at the corners and spaced equally around a circle, representing unique phase shifts for encoding the two bits. However, real-world graphs typically deviate from this ideal due to noise and signal distortion during transmission, causing the points to scatter. Tightly clustered points indicate a good quality channel with minimal noise and distortion, while scattered points suggest a noisy or distorted channel with potential bit errors. Analyzing the spread and clustering of these points away from the ideal positions helps identify channel issues, such as phase or timing errors.

The constellation of filtered points after tracking in Figure 6 shows significant improvement in signal quality compared to previous stages, with points more tightly clustered around four distinct areas, approaching the ideal QPSK positions at (±1, ±1). However, the clusters are still elongated and oriented diagonally, indicating residual phase and amplitude imbalances. This diagonal spread suggests that while tracking has effectively reduced earlier frequency and phase errors, further refinement in phase correction and amplitude equalization is necessary. Additionally, implementing advanced noise reduction techniques could help tighten the clusters and achieve the well-defined points characteristic of a perfectly synchronized QPSK signal.

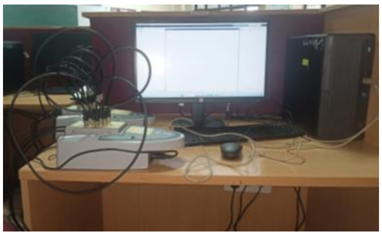

Figure 4. Two WiComm-T connections for transmitting and receiving signals

Table 1. Input given to WiComm-T

Signal receivers	Output
Frequency offset	60 Hz
Phase offset	60°
SNR	20 dB

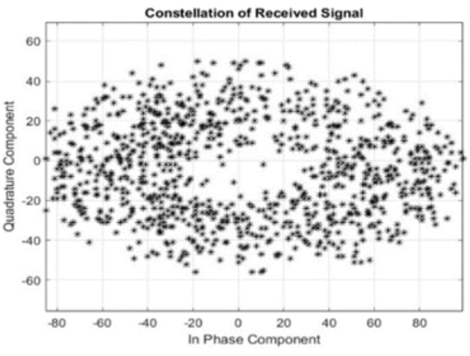

Figure 5. Scatter plot of received symbols of QPSK

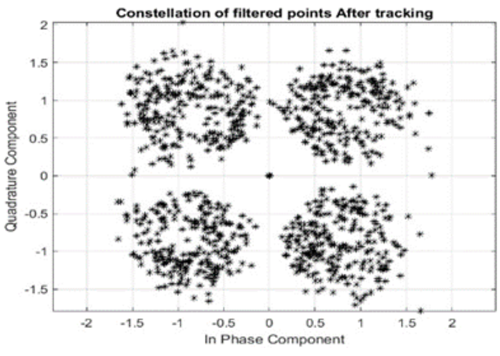

Figure 6. Constellation of filtered points after tracking

4.2. Integration of orthogonal frequency division multiplexing with quadrature phase shift keying

The plot in Figure 7 represents the time-domain function of an OFDM signal, illustrating its real and imaginary parts over a range of sample indices. Both components have amplitudes fluctuating around zero, capturing the complex signal's characteristics. The real part is in blue, while the imaginary part is in orange. Figure 8 depicts the amplitude of an OFDM frame structure with a cyclic prefix over a range of sample indices. The vertical lines with circles on top illustrate the amplitude values, showcasing a varied distribution with some peaks reaching up to 0.16. This visual representation highlights the presence and effect of the cyclic prefix in the OFDM signal.

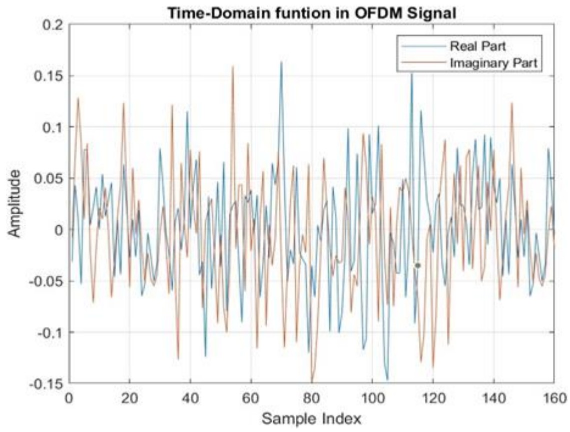

Figure 7. Time-domain function in OFDM

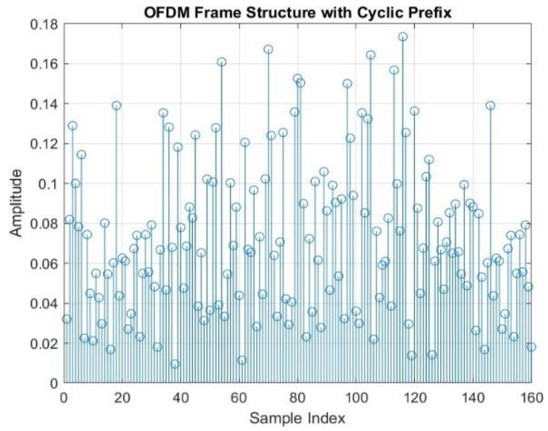

Figure 8. OFDM frame structure with cyclic prefix

Figure 9 illustrates the performance differences between SISO and MIMO systems under varying E_b/N_0 conditions as the signal strength increases (higher E_b/N_0), data transmission errors become less frequent (lower BER). This is crucial for communication systems, as it ensures more reliable data transmission. The comparison of BER and SNR between SISO and MIMO systems at an E_b/N_0 value of -8dB reveals that the SISO system has a BER of 0.12, while the MIMO system has a lower BER of 0.015. Figures 10 and 11 illustrate the performance differences between SISO and MIMO multipath systems under varying E_b/N_0 conditions. The BER performance analysis of experimental and simulated QPSK-OFDM systems at low SNR is given in Table 2.

Our findings indicate that the BER is significantly lower in the present real-time MIMO-OFDM system due to spatial diversity. SISO-OFDM suffers from higher BER under the same conditions due to a lack of diversity. Simulated setups in [22] and [23] show higher BERs, highlighting the gap between simulated and real-time optimized systems. Overall, the results underline the superiority of MIMO in BER performance, especially in real-time environments.

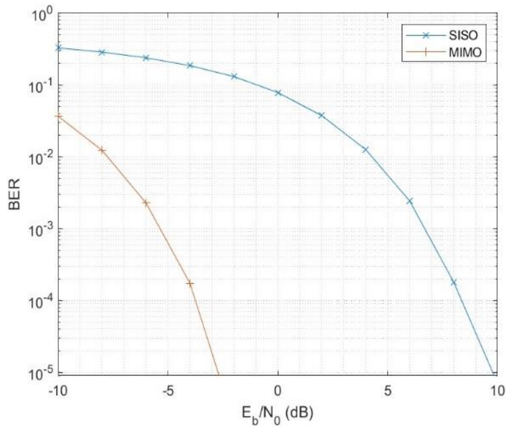

Figure 9. Performance comparison between SISO and MIMO systems

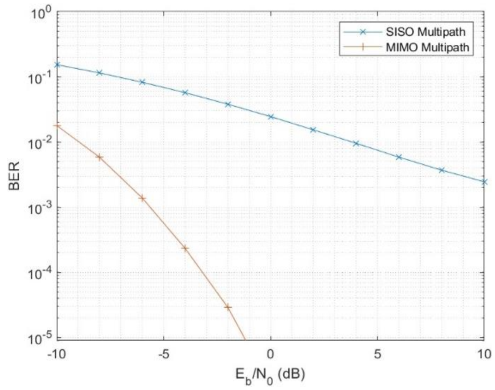

Figure 10. Performance comparison between SISO multipath and MIMO multipath systems

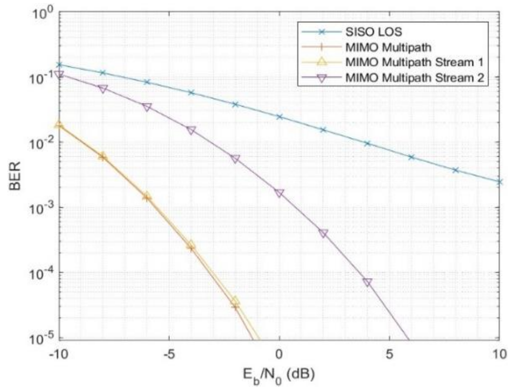

Figure 11. Performance comparison among SISO LOS, MIMO multipath, MIMO multipath stream 1, and MIMO multipath stream 2

Table 2. The BER performance analysis of experimental and simulated QPSK-OFDM systems at low SNR (0 dB)

Setup	BER	Source
2×2 MIMO-OFDM, real-time indoor (QPSK)	0.0002	Present study
SISO-OFDM, real-time indoor (QPSK)	0.05	Present study
OFDM with QPSK over AWGN (simulated)	0.2207	[22]
MIMO-OFDM with QPSK over AWGN (simulated)	~0.12	[23]

5. CONCLUSION

A detailed analysis comparing the performance of SISO and MIMO systems has been conducted. This analysis builds on previous work, which focused solely on SISO configurations. Our findings indicate that the MIMO implementation significantly outperforms the SISO system in terms of BER reduction. Regarding BER, a notable reduction occurs when transitioning from SISO to MIMO configurations. At a lower value of E_b/N_0, the BER for SISO is significantly higher than for MIMO, indicating a substantial difference. Overall, the implementation of MIMO technology has led to a marked improvement in BER and overall efficiency compared to SISO systems. This study reaffirms the advantages of MIMO systems and highlights the potential for future developments in this field. Future work may look into the possible implementation of an indoor wireless environment using USRP boards.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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