Impact of multipath delay and co-channel interference on MIMO and STBC-MIMO

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ABSTRACT

This paper presents a comparative analysis of conventional multiple-input multiple-output (MIMO) systems and space-time block coding (STBC) enhanced MIMO systems across three distinct wireless channel scenarios: flat Rayleigh fading, multipath delay, and multipath delay with co-channel interference. The ability of STBC to exploit multiple independent signal paths between the transmitter and receiver reduces the likelihood of signal fading, which is tried to represent through this work. Using MATLAB simulations, we evaluate system performance under realistic channel conditions, focusing on the key metric of bit error rate (BER). Results show that STBC significantly improves reliability and reduces BER compared to conventional MIMO, particularly under multipath and interference-laden environments.

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1. INTRODUCTION

Multiple-input multiple-output (MIMO) technology has emerged as a cornerstone of modern wireless communications, promising significant improvements in spectral efficiency and reliability without requiring additional bandwidth or transmit power. As wireless networks continue to evolve towards 5G and beyond, the demand for higher data rates, improved reliability, and better coverage has intensified the focus on advanced MIMO techniques. Space-time block coding (STBC), when combined with MIMO systems, offers an attractive solution for enhancing system performance through spatial and temporal diversity.

The fundamental premise of MIMO technology lies in its ability to exploit multipath propagation, traditionally considered a drawback in wireless communications, to create multiple independent spatial channels. This spatial multiplexing capability allows for increased data throughput and improved link reliability. STBC further enhances MIMO systems by introducing temporal diversity, effectively coding the transmitted signals across both space and time dimensions to combat fading and interference.

However, the performance of MIMO-STBC systems is heavily influenced by the characteristics of the wireless channel and the presence of interference. Real-world wireless environments present various challenges, including multipath delay spread and co-channel interference, which can significantly impact system performance. Understanding these effects is crucial for optimal system design and deployment in practical applications.

This research paper presents a comprehensive comparative analysis of conventional MIMO systems and STBC-enhanced MIMO systems under three distinct scenarios that progressively introduce real-world channel impairments. The first scenario examines system performance under ideal conditions with flat Rayleigh fading, providing a baseline for comparison. The second scenario introduces multipath delay effects, reflecting more realistic channel conditions commonly encountered in urban environments. The third scenario combines multipath delay with co-channel interference, representing the most challenging but realistic operating condition in modern wireless networks.

Figure 1 illustrates an M x N MIMO system in Rayleigh fading channels. Through this structured approach, we aim to quantify the performance benefits and trade-offs associated with STBC implementation in MIMO systems across these varying channel conditions. Our analysis focuses on key performance metrics, including bit error rate (BER), channel capacity, and outage probability. The results of this study will provide valuable insights for system designers and network planners in selecting appropriate MIMO configurations for different deployment scenarios.

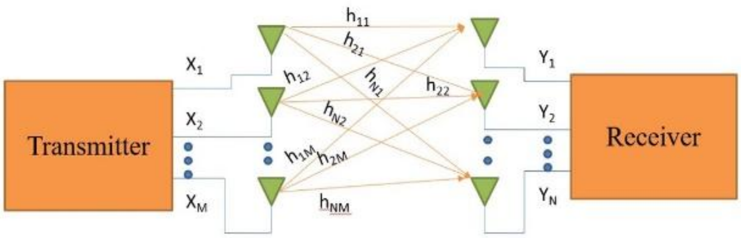

Figure 1. M ×N MIMO system

This investigation is particularly timely given the ongoing deployment of 5G networks and the development of 6G technologies, where advanced MIMO techniques play a crucial role in meeting increasing capacity demands and reliability requirements. Understanding the behavior of MIMO-STBC systems under various channel conditions is essential for optimizing network performance and ensuring robust communication links.

The integration of STBC with MIMO systems has been extensively studied to improve the performance and robustness of wireless communications. STBC enhances system reliability by exploiting spatial and temporal diversity, effectively countering the impacts of fading and interference in MIMO systems. Early theoretical research, including the pioneering work by Alamouti on a simple yet powerful STBC scheme, established the foundation for further exploration in this field [1]. Alamouti's scheme demonstrated the potential of STBC to improve signal reliability under ideal conditions, setting the stage for the development of more advanced STBC techniques.

In recent years, research has increasingly focused on addressing practical challenges such as multipath delay spread, inter-symbol interference (ISI), and co-channel interference, which can significantly degrade the performance of STBC-MIMO systems. For example, Lin [2] proposed tap selection techniques based on orthogonal recursive least squares (ORLS) and Matching Pursuit (MP) algorithms to improve channel equalization in ultra-wideband (UWB) multipath channels affected by ISI and unknown interference. This approach was extended to high-data-rate UWB systems, leveraging receive antenna selection to improve performance under narrowband interference (NBI) conditions.

D'Orazio *et al.* [3] introduced an adaptive minimum-BER approach for multi-user detection (MUD) in STBC-MIMO multi-carrier CDMA systems, demonstrating performance improvements over traditional minimum mean square error (MMSE) adaptive multi-user detection techniques. Their work highlighted the effectiveness of adaptive MUD in enhancing the BER of STBC-MIMO systems in complex multi-user environments. Similarly, Ait-Idir *et al.* [4] examined a turbo packet combining technique for broadband MIMO hybrid-ARQ systems with co-channel interference, showing that under specific conditions, the proposed method could achieve interference resilience.

Further studies have explored the impact of unequal-power co-channel interferers on MIMO beamforming performance. Li *et al.* [5] derived closed-form expressions for the probability density function of interference terms, providing valuable insights into MIMO performance under co-channel interference. Duong and Zepernick [6] focused on cross-layer design for packet data transmission in maximum ratio transmission (MRT) systems with imperfect channel state information (CSI), emphasizing the need for accurate mathematical modeling to address real-world issues affecting MIMO system performance.

Plicanic and Lau [7] investigated the performance of handheld MIMO terminals in urban microcellular environments, examining the effects of noise and interference on capacity. They emphasized that the communication link's power plays a crucial role in determining the capacity of MIMO terminals under noise and interference-limited conditions. In another domain, Zhou *et al.* [8] developed a selective time-reversal receiver for shallow water acoustic MIMO communications, effectively combining time-reversal with multi-channel decision feedback equalization (DFE) to enhance capacity and communication reliability in challenging underwater channels.

Lastly, Wittneben's [9] introduces a novel transmit diversity scheme aimed at improving bandwidth efficiency in wireless communication systems using linear digital modulation. The proposed scheme provides an alternative to conventional diversity techniques by employing modulation-based transmit diversity without requiring additional bandwidth or power.

2. METHOD

This study presents a comparative analysis of conventional MIMO systems and STBC-enhanced MIMO systems under three distinct wireless channel scenarios. The objective is to evaluate the effectiveness of STBC in enhancing system performance across varying channel conditions, providing insights into its benefits under different levels of channel complexity.

2.1. Performance of MIMO system over Rayleigh channel

The first scenario, the flat Rayleigh fading channel, represents an idealized wireless channel with no multipath delay spread or interference. This scenario serves as a baseline for performance comparison, allowing each system configuration to be evaluated under optimal conditions. It provides a clear assessment of the system's core functionality without external signal distortion.

MIMO system is represented in a general form as shown in Figure 1. The received vector y(t) is expressed in terms of the channel transmission matrix h(t) the input vector x(t), and the noise vector n(t) as follows:

$$y(t) = x(t) * h(t) + n(t) \tag{1}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} \quad x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix} \quad \text{h}= \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1M} \\ h_{21} & h_{22} & \dots & h_{2M} \\ h_{31} & h_{32} & \dots & h_{3M} \\ h_{N1} & h_{N2} & \cdots & h_{NM} \end{bmatrix} \quad n = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_M \end{bmatrix} \tag{2}$$

where: y(t) is the received signal vector (size Nr×1),
$x(t)$ is the transmitted signal vector (size Nt×1),
$h(t)$ is the channel matrix (size Nr×Nt),
$n(t)$ is the noise vector (size Nr×1) as shown in matrix (2)

The elements of the channel matrix $h(t)$ represent the complex gains of the channels between each transmit-receive antenna pair. It can be expressed as: $h(t) = [h_{NM}(t)]$ where $h_{NM}(t)$ represents the gain from the M^{th} transmit antenna to the N^{th} receive antenna at time t [10], [11].

2.2. Performance of MIMO system over a multipath delay Rayleigh channel

The second scenario, the multipath delay environment on Rayleigh channel, introduces multipath delay effects, emulating a more realistic urban wireless environment where signal reflections cause delayed versions of the transmitted signal as shown in Figure 2. This setup is designed to test the system's ability to cope with delay-induced inter-symbol interference, a common challenge in urban settings where signals encounter multiple obstacles before reaching the receiver. Here two multiple paths are considered along with fixed delay of 0 and 2 microseconds in respective paths. It has been considered two paths between each transmitting and receiving antenna over the same Rayleigh channel. So, the effect of RMS delay spread due to two multiple paths on receiving signal has been verified. The channel matrix h(t) includes multipath effects with delays.

The received signal $y(t)$ can be expressed as the sum of contributions from all paths plus AWGN [12], [13].

$$y(t) = \sum_{k=1}^{2} h_k(t) * x(t - \tau_k) + n(t) \tag{3}$$

where: $*$ denotes convolution, τ_k is the delay associated with the k^{th} path,
$h_k(t)$ is the impulse response of the k^{th} path
$x(t-\tau_k)$ is delayed input signal
$n(t)$ is Additive white Gaussian Noise
MIMO system can not sustain the Delay spread due to multiple paths over the Rayleigh channel, so signal quality is degraded more.

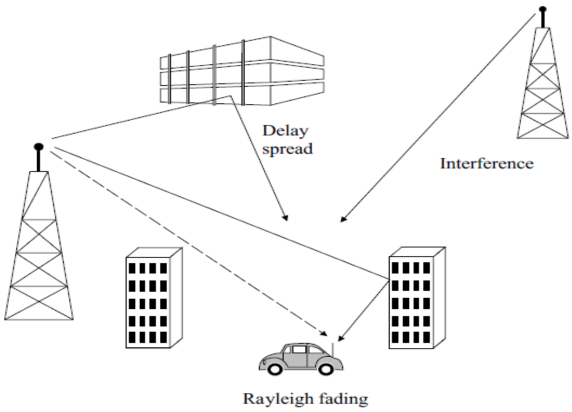

Figure 2. Multipath wireless channel with interference

2.3. Performance of MIMO system over multipath delay rayleigh channel with interferences

The third and most complex scenario is the Multipath Delay with Co-Channel Interference Environment. This setup combines multipath delay with co-channel interference, simulating the intricate conditions of a densely populated urban area where both delayed reflections and interference from other users sharing the same frequency band impact the transmitted signal. This scenario pushes the systems to their limits, providing insight into their performance in highly challenging environments. Here, two different interferences arriving from different angles are considered between each transmitting and receiving antennas over the same multipath RMS delayed Rayleigh channel has been considered for simulation. A simple MIMO system with received signal over multipath delayed channel along with 2 interferences as shown in Figure 2 represented as [14].

$$y(t) = \sum_{k=1}^{2} a(\theta_k) h_k(t)\, x(t-\tau_k) + \sum_{k=1}^{2} a\left(\theta_{k,CCI}\right) h_{k,CCI}(t)\, z(t-\tau_k) + n(t) \quad (4)$$

Where

$$a(\theta_k) = \left[1\ e^{-j\pi sin\theta_k}, \dots\dots, e^{-j\pi(n_R-1)sin\theta_k}\right]^T \quad (5)$$

The antenna array response steering in the direction of arrival θ_k, similarly $a\left(\theta_{k,CCI}\right)$ is the steering angle of co-channel interference. MIMO system performance is degraded more due to interferences and multipath delay environment.

2.4. Performance of STBC system over rayleigh channel

To assess the effectiveness of STBC MIMO, the study evaluated three key performance metrics. BER was calculated as the ratio of incorrectly received bits to the total transmitted bits, serving as a primary measure of system reliability. An STBC system over the Rayleigh Fading Channel was also tested, allowing for an evaluation of the reliability improvements provided by spatial and temporal diversity as shown in Figure 3. Figure 3 shows that STBC symbols S_0, S_1, S_2, and so on are orthogonally transmitted on 2 transmitting antennas and received on a single antenna. STBC enhances the performance of the MIMO system by leveraging spatial and temporal diversity to reduce BER [15], [16].

At time *t* the space-time encoder constructs a matrix of modulated symbols given as:

$$y(t) = H(t)\ x(t) + n(t) \quad (6)$$

$$x(t) = \begin{bmatrix} x_{t,1}^{1} & x_{t,2}^{1} \dots x_{t,k}^{1} \\ x_{t,1}^{2} & x_{t,2}^{2} \dots x_{t,k}^{2} \\ x_{t,1}^{nt} & x_{t,2}^{nt} \dots x_{t,k}^{nt} \end{bmatrix} = STBC\ Symbols$$

Where nt = No of Transmitting Antennas

The matrix $x(t)$ is arranged to encode the transmitted symbols across multiple antennas and time slots. Each row of $x(t)$ corresponds to a specific transmit antenna and each column corresponds to a specific time slot. The matrix $x(t)$ is structured as a $n_t \times k$ matrix,

Where n_t is the number of transmit antennas,

k is the number of STBC symbols per time slot,

$x_{t,1}^{i}, x_{t,2}^{i}, x_{t,k}^{i}$ are the k^{th} STBC-modulated symbols transmitted by the i^{th} transmitting antenna in the t^{th} time slot.

STBC coding is the most effective solution to mitigate the channel impairments occur in more realistic channel in non-line of sight wireless channel. It maintains the signal quality significantly comparative to the simple MIMO channel for different number of antenna configurations. So, it is a great technology in all advanced high data rate wireless systems [17]-[19].

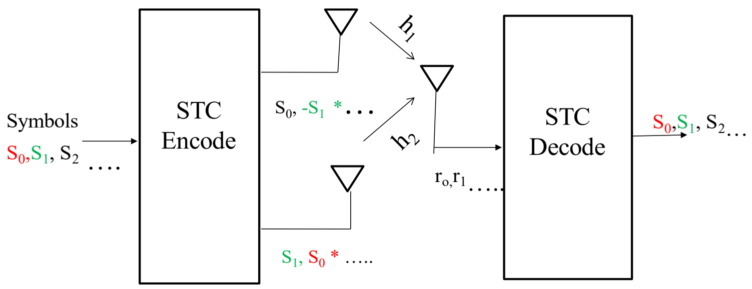

Figure 3. Alamouti 2x1 Space-Time Coding (STC) block diagram

2.5. Performance of STBC system over multipath delayed rayleigh channel

The coding introduces redundancy, improving the system's ability to mitigate errors caused by channel impairments. Implementing STBC in scenarios requiring high reliability and low error rates, particularly in noisy or challenging communication environments is important. STBC is a more effective solution than a standard MIMO system for applications where minimal error rates are critical [20]-[22].

Received STBC Signal over 2 multi-paths with delay.

$$y(t) = \sum_{k=1}^{2} h_k(t)x(t - \tau_k) + n(t) \tag{7}$$

Where k is no of Paths

$h_k = k^{th}$ is the path Rayleigh channel response

$x(t - \tau_k)$ is delayed input STBC signal

Spatial diversity using more antennas at the receiver side than the transmitter side is quite useful to combat the effect of multipath delay over the Rayleigh channel.

2.6. Performance of STBC system over multipath delayed rayleigh channel with interferences

The study's results from these different configurations, across the three-channel scenarios, provided a detailed analysis of the performance gains achieved by integrating STBC MIMO systems. This comparative analysis highlighted the effectiveness of STBC in improving BER, especially in challenging multipath and interference conditions, underscoring its potential to enhance MIMO system performance in real-world, complex environments.

Received signal over multipath channel along with 2 Interferences represented as:

$$y(t) = \sum_{k=1}^{2} a(\theta_k)h_k(t)\, x(t - \tau_k) + \sum_{k=1}^{2} a(\theta_{k,CCI})h_{k,CCI}(t)\, z(t - \tau_k) + n(t) \tag{8}$$

Where $a(\theta_k) = \left[1\ e^{-j\pi sin\theta_k}, \dots \dots \dots, e^{-j\pi(n_R-1)sin\theta_k}\right]^T$

The antenna array response steering in the angle of arrival (AOA) θ_k. Similarly, $a(\theta_{k,CCI})$ is the steering angle of co-channel interference over 2 multiple paths in the Rayleigh channel and $n(t)$ is AWGN noise. STBC is more effective to mitigate the multipath delay and interference challenges over non line of sight wireless channel due to its spatial diversity property [23]-[25].

Simulations were conducted using MATLAB, with parameters carefully chosen to reflect realistic MIMO communication scenarios. The key system parameters included a QPSK modulation scheme, two transmit antennas, four receive antennas, and an SNR range from 0 to 30 dB, with each simulation transmitting a total of 100,000 bits. Two multipath components were defined to simulate multipath conditions, with fixed delays of 0 and 2 microseconds, representing delayed signal reflections. In scenarios involving co-channel interference, additional parameters were introduced to create a realistic interference environment. The angle of arrival for the desired signal was set to 20 degrees, while two interfering signals arrived from -60 and 40 degrees. The interference power was set at -2 dB relative to the desired signal's power, establishing a challenging environment that tests the system's capacity to reject interference while preserving signal integrity.

3. RESULTS AND DISCUSSION

Figure 4 depicts the BER performance versus signal-to-noise ratio (SNR) for three scenarios in a MIMO system: MIMO (without impairments), MIMO with Path Delay, and MIMO with Path Delay and Interferences. MIMO without channel impairments demonstrates the best performance compared to other channel conditions. The BER for MIMO + Path delay indicates a higher BER than the baseline MIMO system due to the effects of path delay. While the BER still decreases with increasing SNR, the degradation caused by path delay results in reduced overall performance. In MIMO + Path delay along with interference scenario exhibits the worst BER performance, as the combined effects of path delay and interference degrade the system significantly. The BER remains almost constant for a wide range of SNR values, indicating that the system struggles to combat interference, even at high SNR levels.

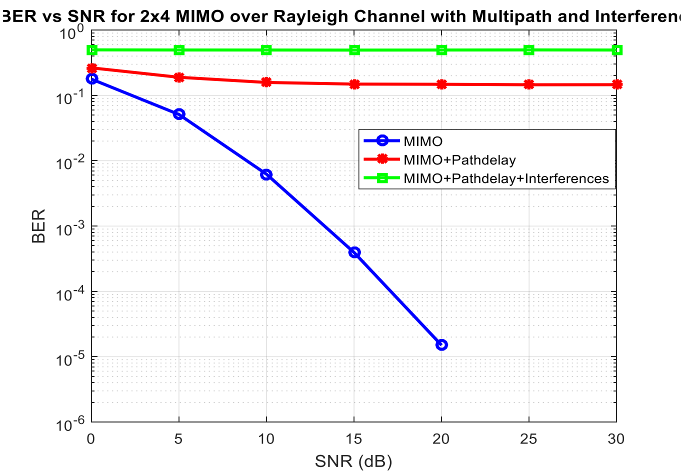

Figure 4. BER Vs SNR for 2 X 4 MIMO system over Rayleigh channel with multipath delay and interferences

Figure 5 depicts the BER performance versus SNR for three scenarios in a STBC system: STBC (without impairments), STBC with Path Delay, and STBC with Path Delay and Interferences. In the first case, the ideal STBC system effectively minimizes BER, leveraging its spatial diversity and robustness in an ideal channel. It demonstrates the best performance among the three scenarios, reaching very low BER values at higher SNRs.

In STBC with Path delays, the inclusion of path delay causes a noticeable degradation in BER performance compared to the ideal STBC system. However, BER still decreases steadily as the SNR increases, indicating that the system can partially combat the effects of path delay. In the third scenario, STBC plus Path delays in the existence of 2 different interferences, the BER decreases with increasing SNR, and the improvement is much slower compared to the other two scenarios, emphasizing the severity of interference on system performance. The presence of both path delay and interference severely impacts the system, indicating that interference is a major limiting factor for STBC performance.

Figure 6 shows the performance of the MIMO and STBC system over an ideal Rayleigh channel. The performance of the MIMO system shows that at lower SNRs, the BER is relatively high, indicating that the system is more prone to errors in noisy conditions. Even at higher SNRs, the BER performance is inferior compared to the STBC system, suggesting limited error correction capabilities in this MIMO configuration. Although MIMO provides diversity gains, it lacks the additional error correction mechanisms present in STBC, resulting in higher BER, especially in low to moderate SNR conditions.

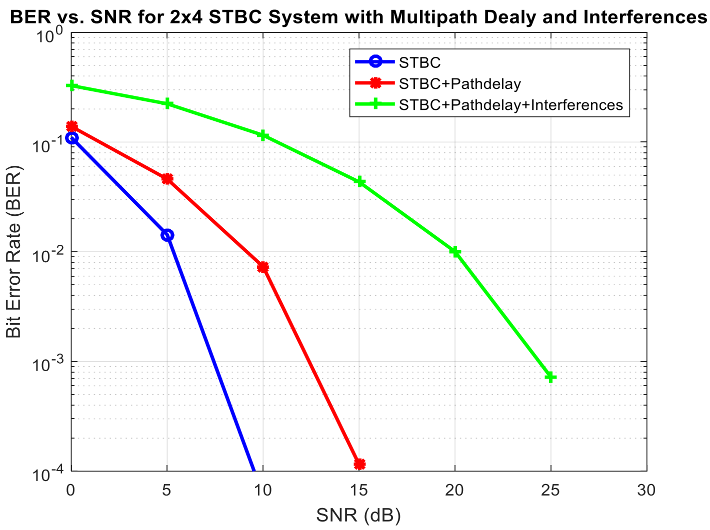

Figure 5. BER Vs SNR for 2 X 4 STBC MIMO over rayleigh channel with multipath delay and interferences

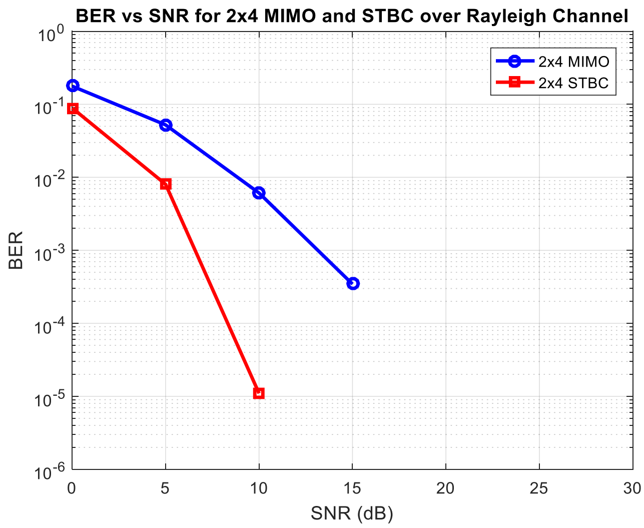

Figure 6. BER Vs SNR for 2 X 4 MIMO and STBC over rayleigh channel with multipath delay and interferences

The BER performance of the STBC system is significantly better than the standard MIMO system at all SNR values. At lower SNRs, the STBC system exhibits a much steeper decline in BER compared to the MIMO system, highlighting the robustness of STBC in handling noise and channel impairments. At higher SNRs, the STBC system achieves near-zero BER, demonstrating superior reliability and effectiveness in minimizing transmission errors.

Figure 7 shows that the STBC system significantly outperforms the MIMO system across all SNR values. The use of STBC seems to provide robustness against the multipath delay, as shown by the lower BER in the red curve. STBC's spatial diversity compensates for the effects of delayed multipath components, which is less effective in the plain MIMO configuration.

Figure 8 shows the BER performance of the MIMO and STBC systems over multipath delay in the existence of the 2 co-channel interferences. At low SNR values, the BER is relatively high, but the system's performance improves drastically with increasing SNR. This trend highlights the effectiveness of the STBC system in mitigating the effects of interference and multipath fading due to its inherent spatial diversity. The results confirm the advantages of STBC in handling challenging channel conditions involving path delays and interference. The MIMO system's performance suffers in such scenarios due to the lack of diversity techniques that can mitigate interference and multipath effects. This highlights the benefits of STBC MIMO technology in enhancing the reliability and robustness of wireless communication systems, which is a key focus of the research described in the paper. The analysis of the impact of multipath delay on the system's reliability provides valuable insights for the design and optimization of robust wireless communication systems.

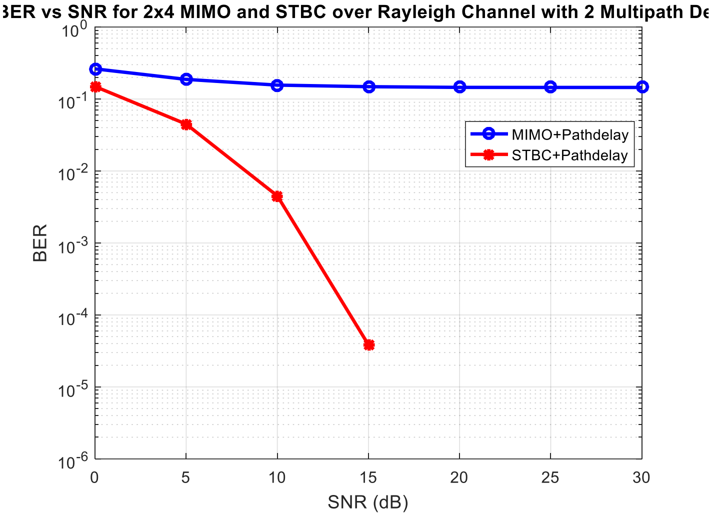

Figure 7. BER Vs SNR for 2 X 4 MIMO and STBC over rayleigh channel with 2 multipath delay and interferences

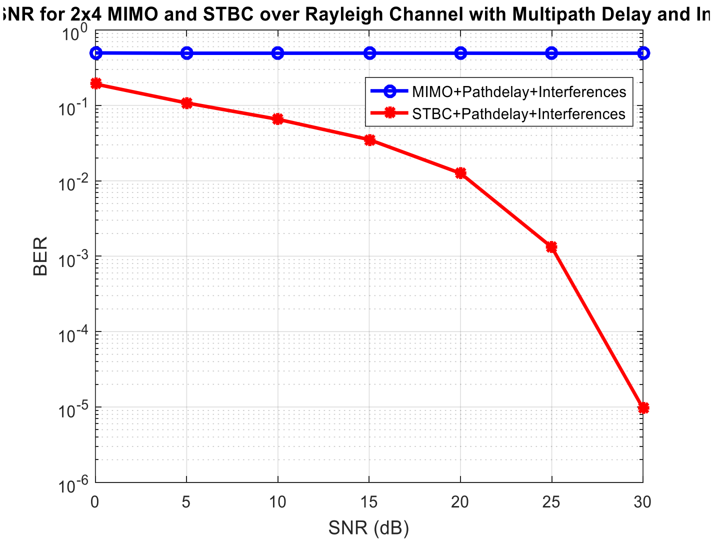

Figure 8. BER Vs SNR for 2 X 4 MIMO and STBC over rayleigh channel with multipath delay and interferences

4. CONCLUSION

This research has presented a comprehensive comparative analysis of conventional MIMO systems and STBC-enhanced MIMO systems across three distinct channel scenarios: flat Rayleigh fading, multipath delay environment, and multipath delay with co-channel interference. MIMO-STBC systems demonstrated significantly enhanced performance over standard MIMO configurations when dealing with multipath fading. In a Rayleigh fading channel with two-path delay, the STBC scheme achieved up to a four-fold reduction in BER compared to conventional MIMO at moderate SNR levels. This reduction highlights STBC's ability to mitigate the impact of fading, offering more reliable communication under conditions that typically degrade signal quality. The technique’s capacity to maintain a low BER under complex channel conditions underscores its potential for deployment in dense urban areas, where interference from other users is a common obstacle. These findings underscore the importance of incorporating advanced MIMO techniques, such as STBC, in future wireless communication systems. The demonstrated improvements in reliability, spectral efficiency, and interference rejection make MIMO-STBC a compelling choice for deployment in 5G and beyond networks, where high data rates, robust coverage, and effective interference management are essential. Future research directions could focus on investigating MIMO-STBC performance under additional real-world channel impairments, such as Doppler effects and non-linear distortions, as well as exploring the integration of these techniques with emerging technologies like massive MIMO and millimetre-wave communications. Such research could further enhance the adaptability and resilience of MIMO-STBC systems in next-generation wireless networks.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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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

- The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].
- The data that support the findings of this study are available from the corresponding author, [Ujwala Bongale], upon reasonable request.

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