Journal of Insights in Basic and Applied Sciences
مجلة رؤى في العلوم الأساسية والتطبيقية
ISSN: 3106-1737
Volume 2, Issue 3, 2026, Pages: 115-126
Journal homepage: https://jibas.com.ly/index.php/jibas/en

Performance Evaluation of Uncoded and Convolutionally Coded Alamouti MIMO Systems for Image Transmission over Rayleigh Fading Channels

Fowzi S. Alarabi [1*], Mustafa Almahdi Algaet[2]
[1,2]Department of Networks, Faculty of Information Technology, Elmergib University, Al-Khoms, Libya

تقييم أداء أنظمة ألاموتي MIMO غير المشفرة والمشفرة بالترميز الالتفافي لإرسال الصور عبر قنوات رايلي المتلاشية

فوزي الصادق العربي[1*], مصطفى المهدي القط[2]
[2,1] قسم الشبكات، كلية تقنية المعلومات، جامعة المرقب، الخمس، ليبيا

[*]Corresponding author: fozuy.alarbi@gmail.com

Received: May 26, 2026	Accepted: June 27, 2026	Published: July 14, 2026

Abstract:

Reliable wireless image transmission over fading channels remains a significant challenge due to the combined effects of multipath propagation and additive noise, which degrade both transmission reliability and reconstructed image quality. This paper presents and evaluates an integrated 2×2 Alamouti multiple-input multiple-output (MIMO) image transmission framework that combines spatial diversity, rate-1/2 convolutional channel coding, and three digital modulation schemes to improve communication reliability over Rayleigh fading channels. Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and 16-Quadrature Amplitude Modulation (16-QAM) are investigated to analyze the trade-off between transmission reliability and spectral efficiency. System performance is evaluated through bit error rate (BER) analysis over a wide range of signal-to-noise ratio (SNR) values, while the quality of the reconstructed images is assessed using the Peak Signal-to-Noise Ratio (PSNR) and the Structural Similarity Index Measure (SSIM). The simulation results demonstrate that the combination of Alamouti space-time block coding and convolutional coding significantly enhances transmission reliability over Rayleigh fading channels. Among the investigated modulation schemes, BPSK achieves the lowest BER together with the highest image reconstruction quality, yielding a PSNR of 58.38 dB and an SSIM of 0.9996 at an operating SNR of 10 dB, whereas comparable image quality is maintained at an SNR of 2 dB when convolutional coding is employed. QPSK provides an effective compromise between transmission reliability and spectral efficiency, whereas 16-QAM offers the highest spectral efficiency at the expense of increased sensitivity to channel impairments. Overall, the obtained results demonstrate that the integration of Alamouti STBC and convolutional coding provides a reliable and computationally efficient approach for wireless image transmission and offers practical design guidelines for selecting appropriate modulation schemes according to application requirements.

Keywords: Alamouti STBC, MIMO, Convolutional Coding, Rayleigh Fading, Image Transmission, BPSK, QPSK, 16-QAM, BER, PSNR, SSIM.

الملخص:
يُعد نقل الصور لاسلكيًا عبر قنوات التلاشي أحد التحديات الرئيسة في أنظمة الاتصالات الحديثة، وذلك بسبب التأثيرات المشتركة لانتشار المسارات المتعددة والضوضاء المضافة، والتي تؤدي إلى تدهور كلٍ من موثوقية الإرسال وجودة الصور المُعاد بناؤها. تقدم هذه الورقة إطارًا متكاملًا لنقل الصور باستخدام نظام تعدد المداخل وتعدد المخارج (MIMO 2×2) المعتمد على ترميز ألاموتي، والذي يجمع بين التنوع المكاني، والترميز الالتفافي بمعدل 1/2، وثلاث تقنيات للتضمين الرقمي بهدف تحسين موثوقية الاتصالات عبر قنوات رايلي المتلاشية
(Rayleigh Fading) وتمت دراسة تقنيات تضمين إزاحة الطور الثنائي (BPSK) ، وتضمين إزاحة الطور الرباعي (QPSK)، وتضمين السعة التربيعية (16 -QAM) لتحليل المفاضلة بين موثوقية الإرسال والكفاءة الطيفية. وقد تم تقييم أداء النظام من خلال تحليل معدل خطأ البتات (BER) عبر مدى واسع من قيم نسبة الإشارة إلى الضوضاء (SNR) ، في حين تم تقييم جودة الصور المُعاد بناؤها باستخدام نسبة ذروة الإشارة إلى الضوضاء (PSNR) ومؤشر التشابه البنيوي (SSIM). وأظهرت نتائج المحاكاة أن الدمج بين ترميز ألاموتي الزمني-المكاني والترميز الالتفافي يُحسن بصورة ملحوظة موثوقية الإرسال عبر قنوات رايلي المتلاشية. ومن بين تقنيات التضمين المدروسة، حقق BPSK أقل معدل لخطأ البتات (BER)، إلى جانب أفضل جودة لإعادة بناء الصورة، حيث بلغت PSNR قيمة 58.38 ديسيبل، وبلغ SSIM قيمة 0.9996عند نسبة إشارة إلى ضوضاء تشغيلية مقدارها 10 ديسيبل، بينما أمكن الحفاظ على جودة إعادة بناء مماثلة للصورة عند نسبة إشارة إلى ضوضاء مقدارها 2 ديسيبل عند استخدام الترميز الالتفافي. كما يوفر QPSK توازنًا فعالًا بين موثوقية الإرسال والكفاءة الطيفية، في حين يحقق 16- QAM أعلى كفاءة طيفية، ولكن على حساب زيادة الحساسية لتشوهات القناة. وبوجه عام، تُظهر النتائج أن دمج ترميز ألاموتي الزمني-المكاني (Alamouti STBC) مع الترميز الالتفافي يوفر أسلوبًا موثوقًا وفعالًا من الناحية الحسابية لنقل الصور لاسلكيًا، كما يقدم إرشادات عملية لاختيار تقنية التضمين المناسبة وفقًا لمتطلبات التطبيق.

الكلمات المفتاحية : ترميز ألاموتي الزمني-المكاني، MIMO، الترميز الالتفافي، تلاشي رايلي، نقل الصور، BPSK، QPSK، 16-QAM، معدل خطأ البتات، PSNR، SSIM.

I. Introduction

Wireless communication systems have experienced remarkable advances in recent years, driven by the rapid growth of multimedia services, mobile communications, wireless sensing applications, and next-generation wireless networks [1], [2]. As a result, reliable wireless image transmission has become an increasingly important research topic because multimedia applications are highly sensitive to transmission errors, fading effects, and channel impairments [3], [4]. Furthermore, the growing demand for real-time image and video services has intensified the need for communication techniques capable of maintaining high reliability and transmission efficiency under adverse channel conditions [5].

In practical wireless environments, transmitted signals are commonly affected by multipath propagation, shadowing, interference, and additive noise. These impairments can significantly degrade signal quality, increase the Bit Error Rate (BER), and reduce the quality of reconstructed multimedia content at the receiver [6], [7]. Consequently, the development of robust communication techniques capable of mitigating fading effects while improving transmission efficiency has attracted considerable attention in recent years [3].

BER is one of the most important performance metrics for evaluating wireless communication systems because it directly reflects transmission reliability and signal detection accuracy [7], [8]. Accurate BER analysis provides valuable insights into the effects of modulation schemes, channel conditions, and antenna configurations on overall system performance. Consequently, BER evaluation through computer simulation has become a widely adopted approach for analyzing communication systems before practical implementation [10].

Digital modulation techniques play a fundamental role in modern wireless communication systems by determining how binary information is mapped onto carrier signals. Different modulation techniques provide different trade-offs among communication reliability, bandwidth utilization, throughput, spectral efficiency, and implementation complexity [9]. Binary Phase Shift Keying (BPSK) is widely recognized for its robustness against noise and fading because of the large Euclidean distance between constellation points. Quadrature Phase Shift Keying (QPSK) improves spectral efficiency by transmitting two bits per symbol while maintaining acceptable BER performance [11], [12]. Higher-order modulation techniques, such as 16-Quadrature Amplitude Modulation (16-QAM), further improve throughput and spectral efficiency by transmitting multiple bits per symbol. However, their performance becomes increasingly sensitive to fading and channel noise due to the reduced Euclidean distance between constellation points [6], [13].

To combat fading effects and improve communication reliability, Multiple-Input Multiple-Output (MIMO) technology has emerged as one of the most effective wireless transmission techniques [14], [15]. By employing multiple antennas at both the transmitter and receiver, MIMO systems exploit spatial diversity to improve signal robustness without requiring additional bandwidth or transmit power [16]. Among various diversity techniques, the Alamouti Space-Time Block Coding (STBC) scheme has attracted considerable attention because of its low computational complexity and its ability to achieve full transmit diversity [17]. The combination of Alamouti STBC with appropriate digital modulation techniques can therefore provide significant BER improvements in fading environments [18].

In addition to spatial diversity, channel coding techniques are widely employed to further enhance transmission reliability. Convolutional coding combined with Soft Decision Viterbi decoding introduces controlled redundancy into the transmitted data stream, enabling the receiver to detect and correct transmission errors more effectively [19], [20]. Such coding techniques are particularly beneficial under severe fading conditions, where uncoded transmission systems typically experience significant performance degradation.

Several previous studies have investigated BER performance for different modulation schemes and wireless channel models. However, most existing studies primarily focus on BER evaluation without simultaneously investigating image reconstruction quality, throughput performance, and spectral efficiency within a unified MIMO wireless image transmission framework [21], [22]. Furthermore, relatively limited attention has been devoted to comparative studies involving both coded and uncoded MIMO systems together with image quality evaluation metrics such as the Peak Signal-to-Noise Ratio (PSNR) and the Structural Similarity Index Measure (SSIM) [23].

Motivated by these observations, this paper presents a comprehensive performance evaluation of uncoded and convolutionally coded 2×2 Alamouti MIMO for wireless image transmission over Rayleigh fading channels. The performance of BPSK, QPSK, and 16-QAM modulation schemes is comparatively analyzed to investigate the trade-off between transmission reliability, throughput, and spectral efficiency. In addition, convolutional coding with Soft Decision Viterbi decoding is employed to evaluate its impact on transmission reliability and reconstructed image quality. System performance is assessed using BER, PSNR, SSIM, throughput, and spectral efficiency, providing a comprehensive evaluation of the relationships among transmission reliability, bandwidth efficiency, and image reconstruction quality under different communication scenarios.

II. System Model

Wireless communication systems transmit information over open-air propagation channels without requiring physical wired connections. They are widely employed in mobile communications, wireless multimedia services, image transmission, wireless sensor networks, and next-generation communication systems. However, wireless channels are inherently affected by noise, interference, and multipath fading, which degrade transmission reliability and received signal quality [24], [25].

To improve communication performance under fading conditions, modern wireless systems employ digital modulation, Multiple-Input Multiple-Output (MIMO) technology, diversity techniques, and channel coding. This paper investigates wireless image transmission using 2×2 Alamouti STBC MIMO combined with different digital modulation schemes over Rayleigh fading channels with AWGN.

2.1 Channel Model

In wireless environments, transmitted signals propagate through multiple paths because of reflection, scattering, and diffraction from surrounding objects. Consequently, the received signal experiences random amplitude and phase variations known as multipath fading [26].

To represent practical propagation conditions, a Rayleigh fading channel with AWGN is considered. The Rayleigh model is appropriate for non-line-of-sight (NLOS) environments, where no dominant propagation path exists between the transmitter and receiver [27], [28]. Accordingly, the received signal is expressed as:

$$r(t) = h(t)s(t) + n(t)$$

where $r(t)$ is the received signal, $h(t)$ is the fading channel coefficient, $s(t)$ represents the transmitted signal, and $n(t)$ denotes the AWGN component.

2.2 MIMO Alamouti STBC System

MIMO technology enhances wireless communication reliability by exploiting spatial diversity through multiple antennas at both the transmitter and receiver, thereby improving signal robustness without requiring additional bandwidth or transmit power [17].

Among various MIMO techniques, Alamouti STBC is widely used because of its simple implementation, low computational complexity, and full transmit diversity capability [29]–[31]. This paper employs a 2×2 Alamouti STBC MIMO system for wireless image transmission. The Alamouti encoder transmits two symbols over two consecutive time slots according to the following transmission matrix.

$$S = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

where s_1 and s_2 are the transmitted complex symbols, and s^* denotes the complex conjugate operation.

The use of Alamouti STBC provides spatial diversity gain, significantly improving transmission reliability and reducing BER over fading channels. This improvement is particularly beneficial for wireless image transmission, where transmission errors directly affect the quality of the reconstructed image.

2.3 Digital Modulation Schemes

Digital modulation determines how binary information is mapped onto carrier signals and directly influences transmission reliability, throughput, and spectral efficiency [32]. In this paper, three modulation schemes are investigated: BPSK, QPSK, and 16-QAM, representing low-, medium-, and high-order modulation formats, respectively.

A. Binary Phase Shift Keying (BPSK)

BPSK transmits one bit per symbol using two phase states separated by 180°. Owing to the maximum Euclidean distance between constellation points, it provides the highest robustness against noise and fading, resulting in the lowest BER among the investigated modulation schemes [33]. However, its spectral efficiency is limited to one bit per symbol.

B. Quadrature Phase Shift Keying (QPSK)

QPSK conveys two bits per symbol using four phase states, doubling the spectral efficiency of BPSK while maintaining good BER performance under moderate channel conditions [32]. Consequently, it provides a practical compromise between transmission reliability and bandwidth efficiency.

C. 16-Quadrature Amplitude Modulation (16-QAM)

16-QAM transmits four bits per symbol by combining amplitude and phase variations, providing the highest throughput and spectral efficiency among the investigated modulation schemes [34]. However, the reduced Euclidean distance between constellation points increases its sensitivity to noise and fading, requiring higher SNR values to achieve reliable performance.

These modulation schemes provide different trade-offs between transmission reliability, throughput, and spectral efficiency, making them suitable for evaluating wireless image transmission under different channel conditions.

2.4 Channel Coding

Channel coding is widely employed to improve transmission reliability in noisy and fading environments. In this paper, a rate-1/2 convolutional code with Soft Decision Viterbi decoding is employed to reduce transmission errors and improve BER performance.

Convolutional coding introduces controlled redundancy into the transmitted bit stream, enabling more reliable error correction at the receiver [35]. Soft Decision Viterbi decoding further improves decoding accuracy by exploiting the reliability information contained in the received symbols rather than making hard binary decisions, thereby providing superior error-correction performance compared with conventional hard-decision decoding [36].

3. Performance Metrics

The performance of wireless image transmission systems cannot be adequately evaluated using a single metric because both communication reliability and reconstructed image quality must be considered. Therefore, this paper evaluates system performance using BER, PSNR, SSIM, throughput, and spectral efficiency. These metrics provide a comprehensive assessment of transmission reliability, bandwidth utilization, and image reconstruction quality under different modulation schemes and coding configurations.

1 Image Quality Metrics

Channel impairments such as fading and noise introduce transmission errors that degrade the quality of reconstructed images. To objectively evaluate image reconstruction performance, PSNR and SSIM are employed.

A. Peak Signal-to-Noise Ratio (PSNR)

PSNR is a widely used objective metric that measures the similarity between the original and reconstructed images based on the mean squared error (MSE) [23]. Higher PSNR values indicate lower distortion and better image reconstruction quality. It is calculated as

$$\mathrm{PSNR} = 10\log_{10}\left(\frac{\mathrm{MAX}^2}{\mathrm{MSE}}\right)$$

where MAX is the maximum pixel intensity and MSE is the mean squared error between the original and reconstructed images.

B. Structural Similarity Index Measure (SSIM)

While PSNR quantifies pixel-wise distortion, SSIM evaluates image quality according to human visual perception by jointly considering luminance, contrast, and structural similarity [37]. SSIM ranges from 0 to 1, with values closer to 1 indicating higher structural similarity and better reconstructed image quality.

3.2 Bit Error Rate (BER)

BER is a fundamental performance metric that quantifies transmission reliability by measuring the ratio of erroneous bits to the total number of transmitted bits [38]. Lower BER values indicate improved communication performance and greater robustness against fading and noise.

BER is defined as

$$BER = \frac{N_e}{N_t}$$

where N_e is the number of erroneous bits, N_t is the total number of transmitted bits.

In this paper, BER is evaluated over a wide range of SNR values to investigate the effects of modulation schemes, Alamouti STBC, and convolutional coding on transmission reliability.

3.3 Throughput and Spectral Efficiency

Throughput represents the effective information rate successfully received after accounting for transmission errors [39]. It is evaluated as

$$\mathrm{Throughput} = R(1 - BER)$$

where R is the transmission rate.

Spectral efficiency measures the amount of information transmitted per unit bandwidth [40]. For the investigated modulation schemes, the nominal spectral efficiencies are 1, 2, and 4 b/s/Hz for BPSK, QPSK, and 16-QAM, respectively. Consequently, higher-order modulation schemes provide higher throughput and bandwidth efficiency, whereas lower-order modulation schemes generally offer better transmission reliability. This trade-off is further analyzed in the Results and Discussion section.

4. Results and Discussion

The performance of the investigated 2×2 Alamouti MIMO image transmission system was evaluated over Rayleigh fading channels using BPSK, QPSK, and 16-QAM modulation schemes. The evaluation was conducted in two stages. First, the BER performance of the uncoded and convolutionally coded systems was analyzed over a wide range of SNR values. Subsequently, image transmission performance was assessed using PSNR and SSIM to examine the relationship between communication reliability and reconstructed image quality. Finally, the trade-off between reliability, throughput, and spectral efficiency was discussed to evaluate the suitability of each modulation scheme for different wireless communication scenarios.

4.1 BER Performance of Uncoded MIMO Transmission

Figure 1 presents the BER performance of the uncoded 2×2 Alamouti MIMO system employing BPSK, QPSK, and 16-QAM over a Rayleigh fading channel. As shown, the BER decreases continuously with increasing SNR for all modulation schemes, demonstrating the effectiveness of Alamouti spatial diversity in mitigating fading-induced errors.

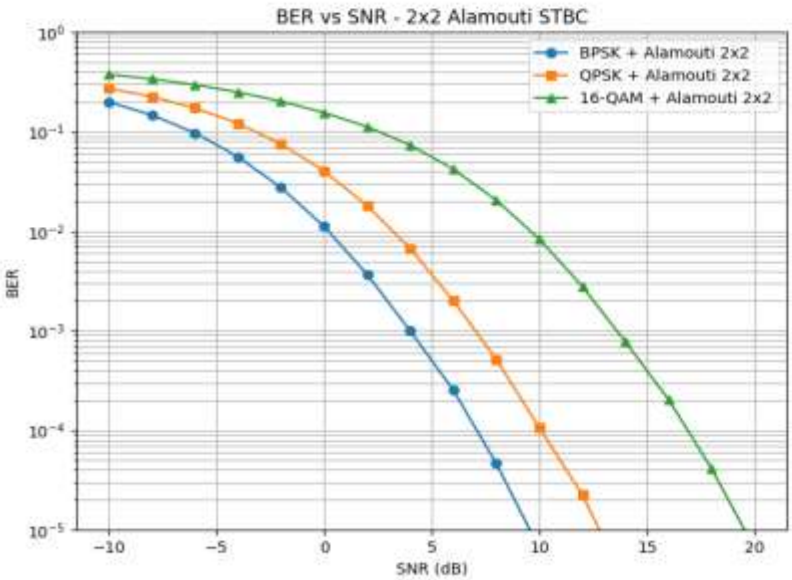

Figure 1: BER performance of the uncoded 2×2 Alamouti MIMO system.

Among the investigated modulation schemes, BPSK consistently achieves the lowest BER throughout the entire SNR range owing to the maximum Euclidean distance between its constellation points. This characteristic provides superior robustness against channel fading and additive noise, making BPSK the most reliable modulation scheme, particularly at low and moderate SNR values.

QPSK exhibits slightly higher BER than BPSK while doubling the number of transmitted bits per symbol. This behavior provides an effective compromise between transmission reliability and bandwidth efficiency, making QPSK well suited for applications requiring both reliable communication and moderate data rates.

By contrast, 16-QAM demonstrates the highest BER because its dense constellation reduces the minimum Euclidean distance between adjacent symbols, thereby increasing the probability of symbol detection errors under fading and noisy channel conditions. Nevertheless, the higher modulation order substantially improves the achievable throughput and spectral efficiency.

4.2 BER Performance of Coded MIMO Transmission

To improve transmission reliability, rate-1/2 convolutional coding with Soft Decision Viterbi decoding was incorporated into the 2×2 Alamouti MIMO system. Figure 2 compares the BER performance of the coded system for BPSK, QPSK, and 16-QAM over the same Rayleigh fading channel

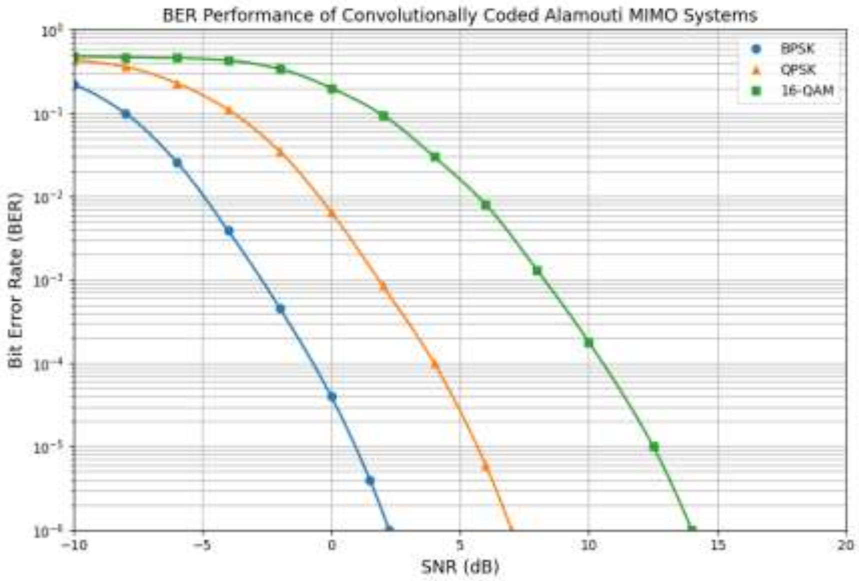

Figure 2: BER performance of the convolutionally coded 2×2 Alamouti MIMO system.

As illustrated in Figure 2 channel coding significantly reduces the BER for all investigated modulation schemes, with the greatest improvement observed in the low- and moderate-SNR regions where transmission errors are most severe. This improvement results from the redundancy introduced by convolutional coding, which enables the Viterbi decoder to detect and correct a substantial proportion of channel-induced errors.

Among the investigated modulation schemes, BPSK achieves the best BER performance after coding, followed by QPSK, while 16-QAM continues to exhibit the highest BER because of its higher sensitivity to fading and noise. Nevertheless, all modulation schemes benefit from channel coding, confirming its effectiveness in enhancing communication reliability.

The obtained results also demonstrate that the combination of Alamouti spatial diversity and convolutional coding provides complementary protection against channel impairments. While Alamouti STBC mitigates multipath fading through spatial diversity, convolutional coding reduces the residual transmission errors through forward error correction. The resulting diversity and coding gains substantially improve system robustness without increasing the transmission bandwidth or transmit power.

4.3 Image Transmission Performance

To further assess the practical performance of the investigated transmission schemes, grayscale image transmission experiments were conducted using the 2×2 Alamouti MIMO system. While the BER results provide a quantitative measure of transmission reliability, image reconstruction quality was evaluated using PSNR and SSIM, which jointly assess objective distortion and perceptual image quality.

Figure 3 presents the reconstructed images obtained using the uncoded system with (a) BPSK, (b) QPSK, and (c) 16-QAM at an operating SNR of 10 dB. For each modulation scheme, the corresponding BER, PSNR, and SSIM values were used to evaluate transmission performance.

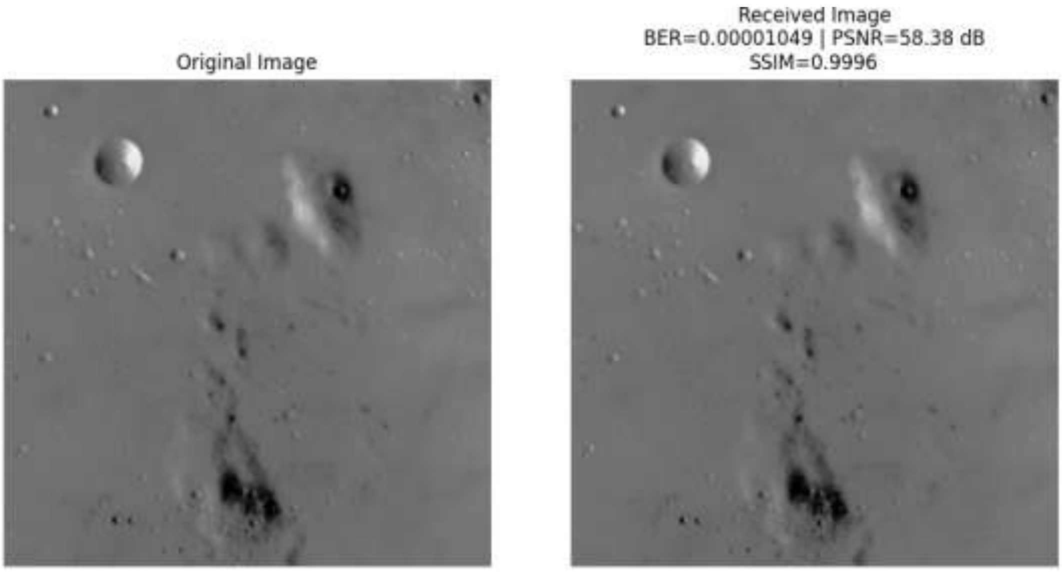

Figure 3(a): BPSK image transmission (SNR = 10 dB).

As shown in Fig. 3(a), BPSK achieves the highest reconstruction quality, producing the lowest BER together with the highest PSNR and SSIM values. Consequently, the reconstructed image is visually almost indistinguishable from the original image, demonstrating the excellent robustness of BPSK against Rayleigh fading and additive noise.

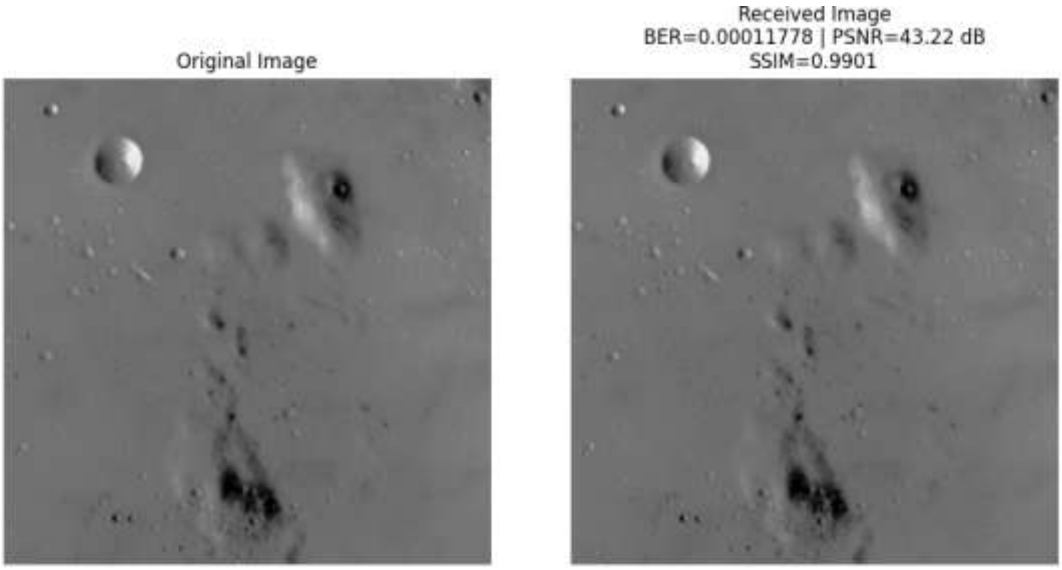

Figure 3(b): QPSK image transmission (SNR = 10 dB).

The image reconstructed using QPSK, shown in Fig. 3(b), also exhibits high visual quality with only a slight reduction in PSNR and SSIM compared with BPSK. Despite transmitting twice as many bits per symbol, QPSK preserves most structural image details, providing an effective balance between transmission reliability and spectral efficiency.

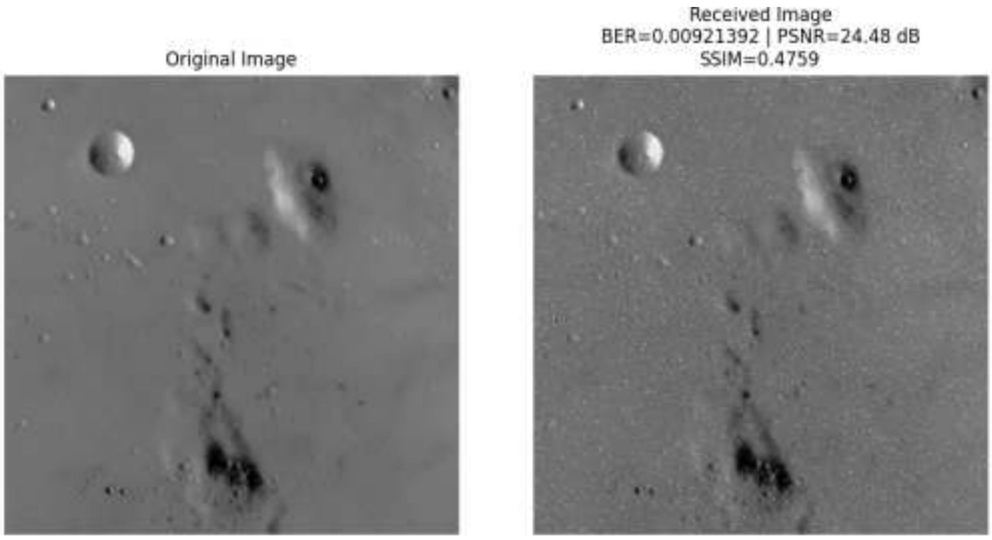

Figure 3(c): 16-QAM image transmission (SNR = 10 dB).

As illustrated in Fig. 3(c), 16-QAM exhibits more noticeable image degradation because of its higher BER under identical channel conditions. The lower PSNR and SSIM values result in visible distortions, particularly around edges and fine image details. Nevertheless, the reconstructed image remains clearly recognizable, demonstrating that higher-order modulation can still support acceptable image transmission when combined with Alamouti spatial diversity.

To further evaluate the impact of channel coding, Figure 4 shows the reconstructed image obtained using rate-1/2 convolutionally coded BPSK with Soft-Decision Viterbi decoding at an operating SNR of 2 dB.

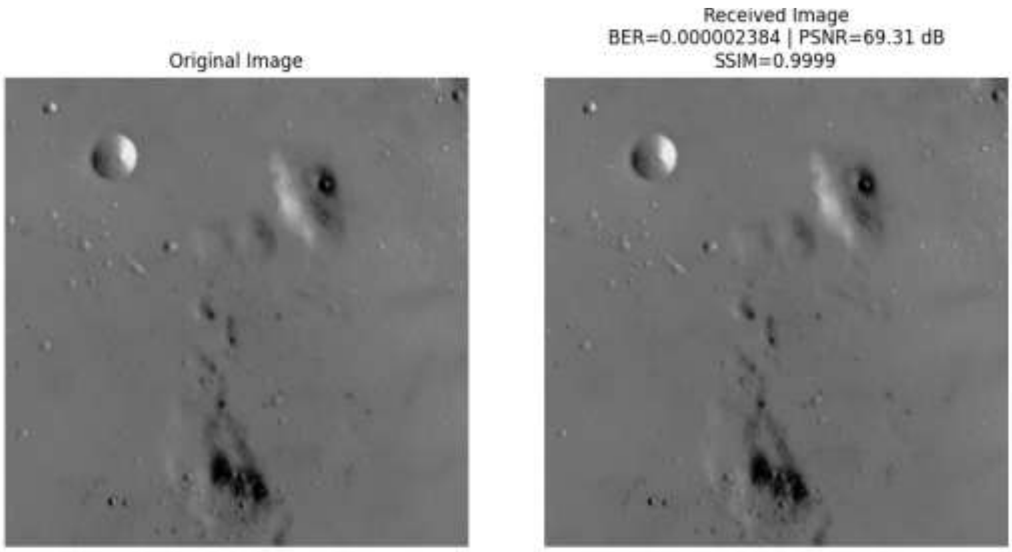

Figure 4: BPSK image transmission with convolutional coding (SNR = 2 dB).

Despite the substantially lower operating SNR, the reconstructed image maintains excellent visual quality with a very low BER and high PSNR and SSIM values. Compared with the uncoded transmission at 10 dB, image quality is largely preserved even at 2 dB, demonstrating the significant coding gain achieved by the convolutional coding scheme.

This improvement results from the complementary operation of Alamouti STBC and forward error correction. While Alamouti STBC mitigates multipath fading through spatial diversity, convolutional coding enables the Viterbi decoder to correct a large proportion of residual transmission errors. Their combined effect significantly improves communication reliability and preserves image quality under challenging channel conditions.

4.4 Coding Gain and Performance Trade-Off

The obtained results demonstrate the inherent trade-off between transmission reliability and spectral efficiency in wireless MIMO communication systems. Among the investigated modulation schemes, BPSK consistently provides the lowest BER and the highest reconstructed image quality, confirming its superior robustness under Rayleigh fading conditions. In contrast, 16-QAM achieves the highest throughput and spectral efficiency by transmitting four bits per symbol, but at the expense of increased sensitivity to channel impairments and higher BER. QPSK offers an effective compromise, combining relatively low BER with improved bandwidth efficiency, making it well suited for applications requiring both reliable transmission and moderate data rates.

A key outcome of this study is the significant improvement achieved through convolutional coding. The coded system consistently outperforms its uncoded counterpart over the entire SNR range, with the largest improvement observed at low and moderate SNR values. This behavior confirms the effectiveness of forward error correction in reducing transmission errors under challenging channel conditions.

The coding gain is further verified by the image transmission results. While the uncoded BPSK system achieves excellent image quality at an operating SNR of 10 dB, comparable visual quality is maintained when convolutional coding is employed at 2 dB. This result demonstrates that channel coding extends reliable system operation to substantially lower SNR values while preserving high image reconstruction quality.

The integration of Alamouti STBC and convolutional coding provides complementary diversity and coding gains, significantly enhancing transmission reliability without increasing transmission bandwidth or transmit power. These results demonstrate that the combination of spatial diversity and forward error correction is an effective approach for achieving reliable wireless image transmission over fading channels.

Conclusion

This paper presented a comprehensive performance evaluation of a 2×2 Alamouti MIMO wireless image transmission system employing BPSK, QPSK, and 16-QAM modulation schemes over Rayleigh fading channels. To enhance transmission reliability, rate-1/2 convolutional coding with Soft Decision Viterbi decoding was incorporated, and its impact was investigated through BER analysis together with objective image quality assessment using PSNR and SSIM.

The simulation results demonstrate that the combined use of Alamouti STBC and convolutional coding significantly improves communication reliability under fading conditions. Among the investigated modulation schemes, BPSK achieved the lowest BER together with the highest reconstructed image quality, whereas QPSK provided an effective compromise between reliability and spectral efficiency. 16-QAM offered the highest spectral efficiency and throughput at the expense of increased sensitivity to channel impairments.

A key outcome of this work is the significant coding gain achieved through convolutional coding. Comparable image quality was maintained at an operating SNR of 2 dB with channel coding, compared with the uncoded transmission at 10 dB, demonstrating the effectiveness of forward error correction in extending reliable system operation to lower SNR conditions. The close agreement between the BER, PSNR, and SSIM results further confirms that improvements in communication reliability directly translate into enhanced reconstructed image quality. The presented results demonstrate that the integration of Alamouti STBC, convolutional coding, and appropriate modulation selection provides an effective and computationally efficient solution for reliable wireless image transmission over fading channels. Future work may investigate more advanced channel coding techniques, such as LDPC and Turbo codes, adaptive modulation schemes, higher-order MIMO configurations, and OFDM-based transmission to further enhance reliability, spectral efficiency, and multimedia quality.

References

[1] Rappaport, T. S. (2002). *Wireless communications: Principles and practice* (2nd ed.). Prentice Hall.

[2] Goldsmith, A. (2005). *Wireless communications*. Cambridge University Press.

[3] Tse, D., & Viswanath, P. (2005). *Fundamentals of wireless communication*. Cambridge University Press.

[4] Molisch, A. F. (2022). *Wireless communications: From fundamentals to beyond 5G* (3rd ed.). Wiley.

[5] Ge, X., Cheng, H., Guizani, M., & Han, T. (2014). 5G wireless backhaul networks: Challenges and research advances. *IEEE Network*, *28*(6), 6–11.

[6] Simon, M. K., & Alouini, M.-S. (2005). *Digital communication over fading channels* (2nd ed.). Wiley.

[7] Basudewa, M., et al. (2020). Bit error rate performance analysis for free space optic communication. *IOP Conference Series: Materials Science and Engineering*.

[8] Proakis, J. G., & Salehi, M. (2008). *Digital communications* (5th ed.). McGraw-Hill.

[9] Sklar, B. (2021). *Digital communications: Fundamentals and applications* (3rd ed.). Pearson.

[10] Shankar, P. M. (2017). Modems for wireless communications. In *Fading and shadowing in wireless systems* (pp. 213–297). Springer.

[11] Hasan, M. D., Sarker, S., & Alam, A. (2017). *Performance analysis of BPSK and QPSK under Rayleigh fading channel* (Bachelor's dissertation). Department of Electrical and Electronic Engineering, East West University.

[12] Obinna, O., Kennedy, O., Osemwegie, O., & Nsikan, N. (2017). Comparative analysis of channel estimation techniques in SISO, MISO and MIMO systems. *International Journal of Electronics and Telecommunications, 63*(3), 299–304.

[13] Kishore, G. S., & Rallapalli, H. (2019). Performance assessment of M-ary ASK, FSK, PSK, QAM and FQAM in AWGN channel. In *Proceedings of the 2019 International Conference on Communication and Signal Processing (ICCSP)* (pp. 273–277). IEEE.

[14] Paulraj, A., Nabar, R., & Gore, D. (2003). *Introduction to space-time wireless communications*. Cambridge University Press.

[15] Gesbert, D., Shafi, M., Shiu, D. S., Smith, P. J., & Naguib, A. (2003). From theory to practice: An overview of MIMO space-time coded wireless systems. *IEEE Journal on Selected Areas in Communications, 21*(3), 281–302.

[16] Duman, T. M., & Ghrayeb, A. (2008). *Coding for MIMO communication systems*. Wiley.

[17] Alamouti, S. M. (1998). A simple transmit diversity technique for wireless communications. *IEEE Journal on Selected Areas in Communications, 16*(8), 1451–1458.

[18] Tarokh, V., Jafarkhani, H., & Calderbank, A. R. (1999). Space-time block codes from orthogonal designs. *IEEE Transactions on Information Theory, 45*(5), 1456–1467.

[19] Gautam, A., Thakur, P., & Singh, G. (2024). Advanced channel coding schemes for B5G/6G networks: State-of-the-art analysis, research challenges and future directions. *International Journal of Communication Systems, 37*, e5855. https://doi.org/10.1002/dac.5855

[20] Viterbi, A. J. (1967). Error bounds for convolutional codes and an asymptotically optimum decoding algorithm. *IEEE Transactions on Information Theory, 13*(2), 260–269.

[21] Kumar, R., & Saxena, R. (2014). Performance analysis of MIMO-STBC systems with higher coding rate using adaptive semiblind channel estimation scheme. *The Scientific World Journal, 2014*, Article 304901.

[22] Gupta, A., Dogra, S., & Sofi, I. B. (2019). Performance evaluation of spatial multiplexing using different modulation techniques in MIMO systems for small- and large-scale fading channels. *International Journal of Sensors, Wireless Communications and Control, 9*(2), 188–202.

[23] Wang, Z., Bovik, A. C., Sheikh, H. R., & Simoncelli, E. P. (2004). Image quality assessment: From error visibility to structural similarity. *IEEE Transactions on Image Processing, 13*(4), 600–612.

[24] Panić, S., Stefanović, M., Anastasov, J., & Spalević, P. (2013). *Fading and interference mitigation in wireless communications*. CRC Press.

[25] Tashatov, N. N., Seksembayeva, M. A., Ovechkin, G., Satybaldina, D., & Seitkulov, Y. N. (2022). Interference immunity and energy efficiency of digital communication systems in multipath fading channels. *Indonesian Journal of Electrical Engineering and Computer Science, 27*(3), 1412–1418.

[26] Sklar, B. (1997). Rayleigh fading channels in mobile digital communication systems. *IEEE Communications Magazine, 35*(7), 90–100.

[27] Simon, M. K., & Alouini, M.-S. (2005). *Digital communication over fading channels* (2nd ed.). Wiley.

[28] Maheswari, E. M., Selvabharathi, S., & Subasri, V. (2020). An end-to-end simulation of wireless communication through AWGN and fading channels. *International Journal of Creative Research Thoughts, 8*(4).

[29] Bharati, S., Podder, P., Gandhi, N., & Abraham, A. (2020). *Realization of MIMO channel model for spatial diversity with capacity and SNR multiplexing gains*. arXiv. https://arxiv.org/abs/2005.02124

[30] Araújo, F. V. J., García-Naya, J., González-López, M., Castedo, L., & Garcia-Frías, J. (2011). Experimental evaluation of MIMO coded modulation systems: Are space-time block codes really necessary? In *MIMO systems*. IntechOpen. https://doi.org/10.5772/15287

[31] Hampton, J. R. (2013). *Introduction to MIMO communications*. Cambridge University Press.

[32] Ahmed, M. F., Ahmed, M. F., & Islam, A. M. T. (2021). Comparison of bit error rate performance of various digital modulation schemes over AWGN and Rayleigh fading channels using Simulink. *International Journal of Ambient Systems and Applications, 9*(2), 7–16.

[33] Nishtar, Z., & Afzal, J. (2023). BER analysis of BPSK modulation scheme for multiple combining schemes over flat fading channels. *Neutrosophic Systems with Applications, 8*, 1–12.

[34] Khan, R., Khan, Z. U., Taj, S., Khan, S. U., Khan, J., Alturki, N., & Alanazi, S. (2025). Optimizing adaptive modulation techniques using standard propagation models for enhanced wireless communication channels. *Scientific Reports, 15*(1), Article 30796.

[35] Hagenauer, J., & Hoeher, P. (1989, November). A Viterbi algorithm with soft-decision outputs and its applications. In *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM)* (pp. 1680–1686). IEEE.

[36] Arasteh, D. (2006, March). Teaching convolutional coding using MATLAB in communication systems courses. In *Proceedings of GSW*.

[37] Sara, U., Akter, M., & Uddin, M. S. (2019). Image quality assessment through FSIM, SSIM, MSE and PSNR: A comparative study. *Journal of Computer and Communications, 7*(3), 8–18.

[38] Dong, J. (2013). Estimation of bit error rate of any digital communication system (Doctoral dissertation, Télécom Bretagne).

[39] Shen, D., Pan, Z., Wong, K. K., & Li, V. O. K. (2003, March–April). Effective throughput: A unified benchmark for pilot-aided OFDM/SDMA wireless communication systems. In *Proceedings of IEEE INFOCOM* (pp. 1603–1613). IEEE.

[40] Verdú, S. (2002). Spectral efficiency in the wideband regime. *IEEE Transactions on Information Theory, 48*(6), 1319–1343.