Gharyan University Journal of Engineering Science (GUJES)
ISSN (3105-4560)
Website: http://journals.gu.edu.ly
email: gujes@gu.edu.ly

Uplink Performance Enhancement for MU-MIMO Wireless Systems with STBC and Regularized ZF Equalization

Amaal O. Althini[1] [*], Sana Ahmed Abdaljlil [2], Olga Boiprav [3], Amer R. Zerek [4]

[1] Surman College of Science & Technology, Sorman-Libya, asial.mh2013@gmail.com
[2] *Aerospace Information Research Institute CAS, Beijing , China* sana.abdaljlil@mails.ucas.ac.cn
[3] *Belarusian State University of Informatics and Radioelectronics*, Minsk, Belarus smu@bsuir.by,
[4] *Libya Open University Tripoli, Libya* a.zerek@zu.edu.ly

[*] *Corresponding author:* asial.mh2013@gmail.com

Received: 10 January 2026	Accepted: 26 Feb 2026	Published: 15 March 2026

Abstract

This paper presents a robust performance study of uplink Multi-User Multiple-Input Multiple-Output (MU-MIMO) wireless communication system with Space-Time Block Coding (STBC) under Rayleigh fading. The model adopts QPSK modulation and numerically stable Zero-Forcing (ZF) equalizer with regularization to cancel inter-user interference and for better numerical stability. The system is analysed using both BER, user and antenna connection capacity. MATLAB simulations demonstrate that increasing the number of receive antennas significantly improves both BER and capacity. Moreover, the proposed regularized (ZF) detection method outperforms conventional approaches, offering improved robustness and reduced complexity. This study showed the effectiveness of the proposed solution and performance of next generation wireless networks through comparative analysis with other prior MU-MIMO schemes.

Keywords: *STBC, ZF, MU-MIMO*

1. Introduction

Multi-User Multiple-Input Multiple-Output (MU-MIMO) is considered as one of the critical development in modern wireless communication systems, which significantly contributes to the increasing demand for greater data rate and enhanced spectral efficiency. From the fifth-generation (5G) to the future sixth-generation (6G) networks, MU-MIMO enables K users to transmit their data simultaneously to a base station (BS) which is equipped with multiple receive antennas. This spatial multiplexing capability significantly enhances system capacity and supports dense user environments, which are characteristic of future wireless deployments. [1, 2].

However, the concurrent transmission of signals from different users introduces a critical problem: inter-user interference, especially in the uplink direction. In such scenarios, the BS receives overlapping signals that are subject to multipath fading and noise, making signal separation a complex task. Robust receiver design becomes essential to ensure reliable communication. [3].

To mitigate the effects of channel fading and interference, diversity techniques such as Space-Time Block Coding (STBC) are often employed. The Alamouti STBC scheme, in particular, provides full transmit diversity with a simple implementation, making it highly suitable for mobile terminals. On the detection side, Zero-Forcing (ZF) equalization is a common linear technique used to mitigate interference. Nonetheless, conventional ZF involves matrix inversion, which becomes numerically unstable in poorly conditioned channels, thereby degrading bit error rate (BER) performance. [1, 4].

This paper tackles the challenge by implementing a regularized ZF equalization method. It demonstrates improvements in numerical stability and Rayleigh fading performance by augmenting a small regularization term during the matrix inversion step. The system employs QPSK modulation and Alamouti STBC, and its performance is evaluated using MATLAB simulations. The results are benchmarked against traditional systems with significant improvements in BER and channel capacity, particularly with increasing receive antenna count.

2. SYSTEM MODEL AND PROPOSED ARCHITECTURE

This section presents the structural and theoretical foundation of the proposed uplink (MU-MIMO) wireless communication system. The model focuses on a multi-user scenario where several mobile users concurrently send data to a Base Station (BS) over a shared wireless channel. This system aims to achieve spatial diversity and help reduce interference by combining Alamouti STBC encoding at the transmitter with regularized ZF equalization at the receiver. In the considered scenario, K users are each equipped with two transmit antennas.

The base station is equipped with Nr receive antennas, resulting in a total of Nt = 2K transmit antennas across all users. The simultaneous transmission from all users enables uplink spatial multiplexing but introduces significant inter-user interference. Therefore, the receiver must perform reliable separation of the overlapping data streams. [5]

Each user first maps its data onto QPSK symbols and encodes them using the Alamouti STBC scheme. This technique spreads the data over two antennas and two time slots, ensuring orthogonally and full diversity. Due to its linear structure and simplicity, Alamouti STBC is especially suitable for mobile terminals with constrained computational resources. The Alamouti-encoded signals from all users are then transmitted through a Rayleigh flat-fading channel.[6].

The wireless channel is modelled as a narrowband, flat Rayleigh fading modeled, where each channel coefficient between A transmit and receive antenna pair is assumed to follow a complex Gaussian distribution with zero mean and unit variance. The additive noise at the receiver is modeled as complex white Gaussian noise with variance depending on the signal-to-noise ratio (SNR). The receiver is assumed to have perfect channel state information (CSI), which enables accurate equalization and decoding.

An overview of the end-to-end system architecture is depicted in Fig. 1. The base station receives a superimposed signal from all users, which is then passed through a regularized zero-forcing (ZF) equalizer to suppress interference and enhance numerical stability. The equalized signal is subsequently decoded using the STBC decoding process, followed by QPSK demodulation to recover the transmitted bits. This system structure balances complexity and performance and is suitable for practical implementation in dense wireless networks. [3, 7].

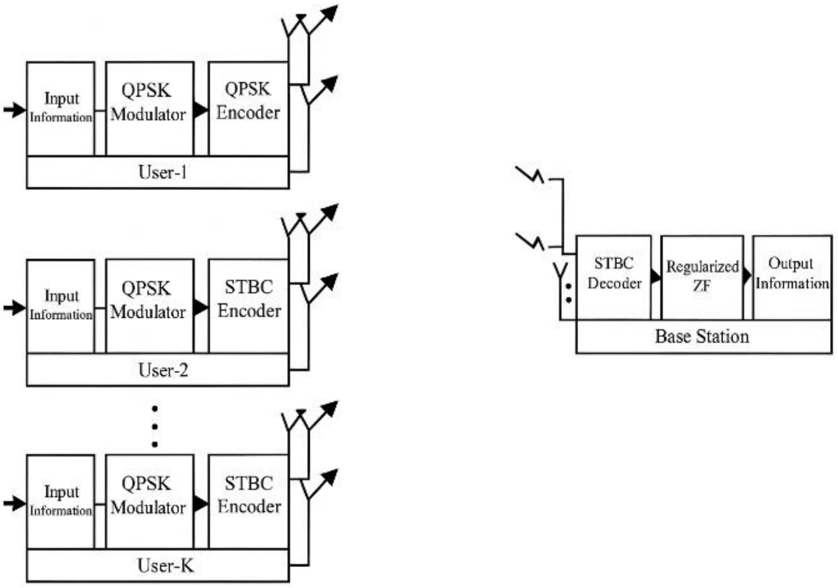


Fig. 1. Block diagram of the proposed uplink MU-MIMO system with STBC and regularized ZF equalization.

3. TBC ENCODING AND REGULARIZED ZF EQUALIZATION

This section presents the signal encoding process using the Alamouti STBC scheme, followed by linear equalization at the base station using a numerically stable regularized ZF detector. The discussion is organized as follows:[4, 8, 9].

A. **Alamouti STBC Structure**

Each user encodes two consecutive QPSK symbols, s_1 and s_2, using the Alamouti space-time block code. The resulting transmission matrix is:

$$X = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{1}$$

This orthogonal design provides full transmit diversity and enables simple linear decoding at the receiver with low computational complexity.

B. **Received Signal Representation**

At the base station, the received signal from all users can be modeled as:[2, 8, 9].

$$Y = H.X + n \tag{2}$$

Where:
Y: {Nr × T} is the received signal matrix,
H: {Nr × Nt} is the Rayleigh fading channel matrix,
X: {Nt × T} is the combined STBC-encoded transmitted signal matrix from all users,
n: {Nr × T} is the additive white Gaussian noise matrix.
This model serves as the input to the equalizer that reconstructs the transmitted data.

C. **Limitations of Conventional ZF Equalization**

Conventional Zero-Forcing (ZF) equalization aims to cancel inter-user interference by inverting the channel matrix H. However, in ill-conditioned channels or under correlated fading, the matrix $H^H \cdot H$ may become nearly singular, resulting in numerical instability and noise amplification. This causes a severe degradation in BER performance.

D. **Regularized ZF Equalizer (Proposed Method)**

To overcome the instability of standard ZF, a regularization term ε·I is added to the matrix inversion, resulting in the following robust equalizer:

$$W_{RZF} = (H^H + \varepsilon I)^{-1} H^H \tag{3}$$

Where:
H^H is the Hermitian transpose of the channel matrix H
I is the identity matrix of size {Nt × Nt}
ε is a small positive constant (e.g., 10^{-6}) used to stabilize the inversion

This method, also known as Tikhonov regularization, guarantees inevitability and mitigates the effects of ill-conditioning.

E. **Decoding and Symbol Recovery**

After equalization, the signal is decoded using the structure of the Alamouti code, which allows the separation of the original QPSK symbols. Final demodulation yields the bit streams transmitted by each user. This detection framework provides improved BER and stable performance in multi-user uplink scenarios.

4. CAPACITY ANALYSIS

In wireless communication systems, channel capacity denotes the maximum information volume that can be sent using a channel without error. For multi-user MIMO systems, especially concerning uplink communication, capacity evaluation is essential for determining the effect of system variables like the user count, receive antennas, and SNR levels on spectral efficiency.[10, 11].

The ergodic capacity of the proposed MU-MIMO system is evaluated under Rayleigh fading conditions. Considering flat-fading and independent realizations of the channel, the system capacity is calculated using the Shannon capacity formula adapted for MIMO architectures: [3, 4,12].

$$C = \log_2 \left(\det \left(I + \frac{SNR}{N_t} \, H \, H^H \right) \right) \tag{4}$$

In this expression, CC denotes the channel capacity in bits per second per Hz, is the channel matrix of size $Nr \times Nt$, $H \; H$ is its Hermitian transpose, Nt is the total number of transmit antennas across all users, Nr is the number of receive antennas at the base station, and SNR is = the average signal-to-noise ratio per receive antenna. The identity matrix$I$ has the dimensions $Nr \times Nr$, ensuring dimensional consistency in the determinant operation. To obtain a meaningful measure of performance under random fading, the capacity is averaged across a large number of independent channel realizations using Monte Carlo simulations. This results in the ergodic capacity, which reflects the long-term average performance of the system in a realistic environment. [8, 11, 13].

Several key insights can be drawn from the capacity model. Increasing the number of receive antennas significantly enhances capacity, as it improves spatial resolution and diversity. Conversely, increasing the number of users without proportionally increasing Nr can reduce per-user capacity due to heightened inter-user interference. Furthermore, as expected from Shannon's theory, capacity improves logarithmically with SNR. The capacity analysis assumes perfect channel state information (CSI) at the receiver, no pilot contamination or channel estimation errors, and an ideal linear detection process based on the regularized ZF equalizer described in Section 3. While real-world deployments may include imperfections, this model serves as a performance benchmark for evaluating the theoretical limits of the proposed system.[4, 7, 9].

Overall, capacity complements BER analysis by providing a broader view of the system's information-theoretic efficiency. A communication scheme that performs well in both metrics is generally considered robust and scalable for high-density wireless environments.[7, 10, 12].

5. SIMULATION SETUP

To evaluate the performance of the proposed uplink MU-MIMO system with Alamouti STBC and regularized ZF equalization, extensive MATLAB simulations were carried out under various system configurations. The simulation environment was designed to reflect practical wireless communication conditions while isolating the effects of system parameters on bit error rate (BER) and channel capacity.

Each user employed QPSK modulation to encode binary data streams, which were then passed through the Alamouti STBC encoder. The encoded signals were transmitted over a flat Rayleigh fading channel with independent fading coefficients for each transmit-receive antenna pair. The base station was configured with multiple receive antennas and perfect channel state information (CSI) was assumed to ensure unbiased detection.

The simulations covered three different user scenarios with K = 1, 2, and 4 users, corresponding to Nt = 2, 4, and 8 total transmit antennas, respectively. For each scenario, the number of receive antennas at the base station (Nr) was varied among 4, 6, and 8 to assess the effect of spatial diversity. The signal-to-noise ratio (SNR) was varied from −10 dB to +20 dB in 2 dB increments.

Each user transmitted 500 QPSK symbols per frame, and a total of 1000 frames were simulated per SNR value to ensure statistically reliable BER and capacity results. The regularization parameter ε used in the ZF equalizer was fixed at 10^{-6} to ensure numerical stability across all simulations.

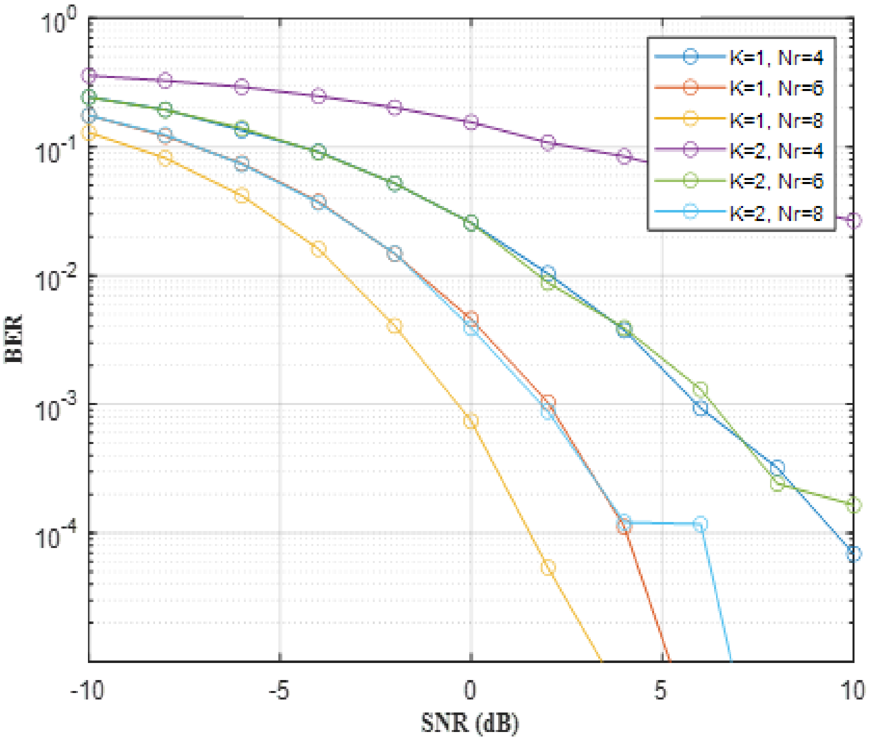
TABLE I. SUMMARY OF SIMULATION PARAMETERS.

Parameter	**Value(S)**
Modulation scheme	QPSK
STBC scheme	Alamouti (2 Tx antennas per user)
Number of users (K)	1, 2, 4
Total transmit antennas (Nt)	2K
Number of receive antennas	4, 6, 8
Channel model	Flat Rayleigh fading
Noise model	AWGN
SNR range	−10 dB to +20 dB (step = 2 dB)
Symbols per user per frame	500
Frames per SNR point	1000
Equalization method	Regularized ZF
Regularization parameter ε	10^{-6}
CSI assumption	Perfect at receiver

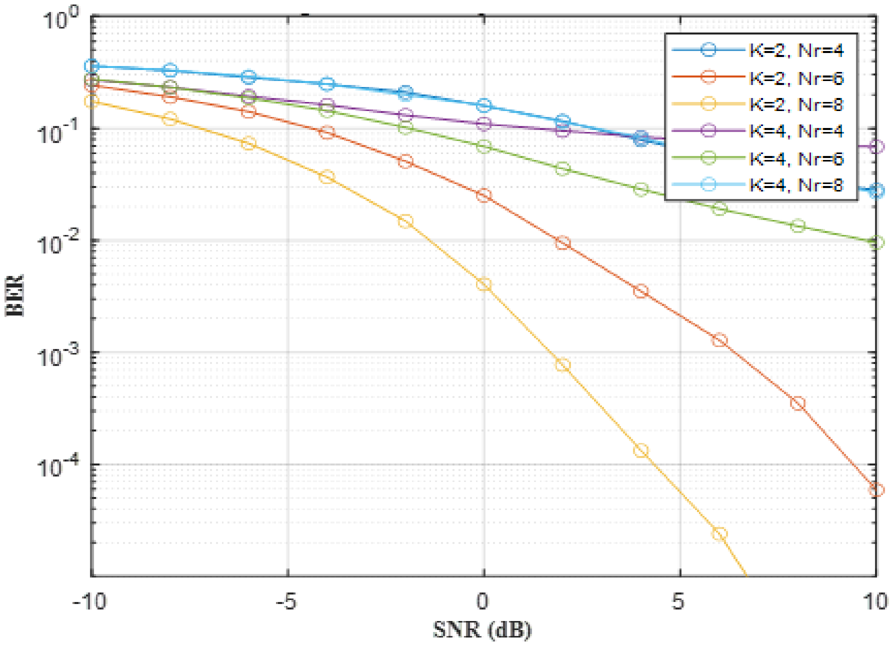
6. RESULTS AND DISCUSSION

This section presents the simulation results for the proposed uplink MU-MIMO system using QPSK modulation, Alamouti STBC encoding, and regularized Zero-Forcing (ZF) equalization. The performance is evaluated in terms of bit error rate (BER) and ergodic channel capacity under varying configurations of user count (K), receive antennas (Nr), and signal-to-noise ratio (SNR).

Fig 2 illustrates the BER performance for multiple scenarios. In Fig. 2(a), BER results are shown for K = 1 and 2 users, with receive antennas Nr = 4, 6, and 8. It is observed that increasing Nr improves BER performance significantly due to enhanced receive diversity. For example, when K = 2 and Nr increases from 4 to 6, the BER at 10 dB SNR drops from approximately 4 × 10^{-3} to 1 × 10^{-3}. Fig. 2(b) extends the analysis to K = 2 and 4 users. As the number of users increases while Nr remains fixed, BER degrades slightly due to increased multi-user interference. Nevertheless, the system maintains stable performance due to the numerical robustness of the regularized ZF decoder.



(a)



(b)

Fig. 2. BER vs. SNR with STBC and regularized ZF equalization: (a) K = 1, 2 user, Nr = 4, 6, 8 (b) K = 2, 4 user, Nr = 4, 6, 8.

In addition to the graphical results, Table II provides sample BER values at key SNR points for different system configurations. These values confirm the effectiveness of increasing both SNR and Nr in reducing BER. Notably, the BER for K = 4 and Nr = 8 reaches near-zero levels even at 10 dB, demonstrating the system’s potential for high-reliability communication.

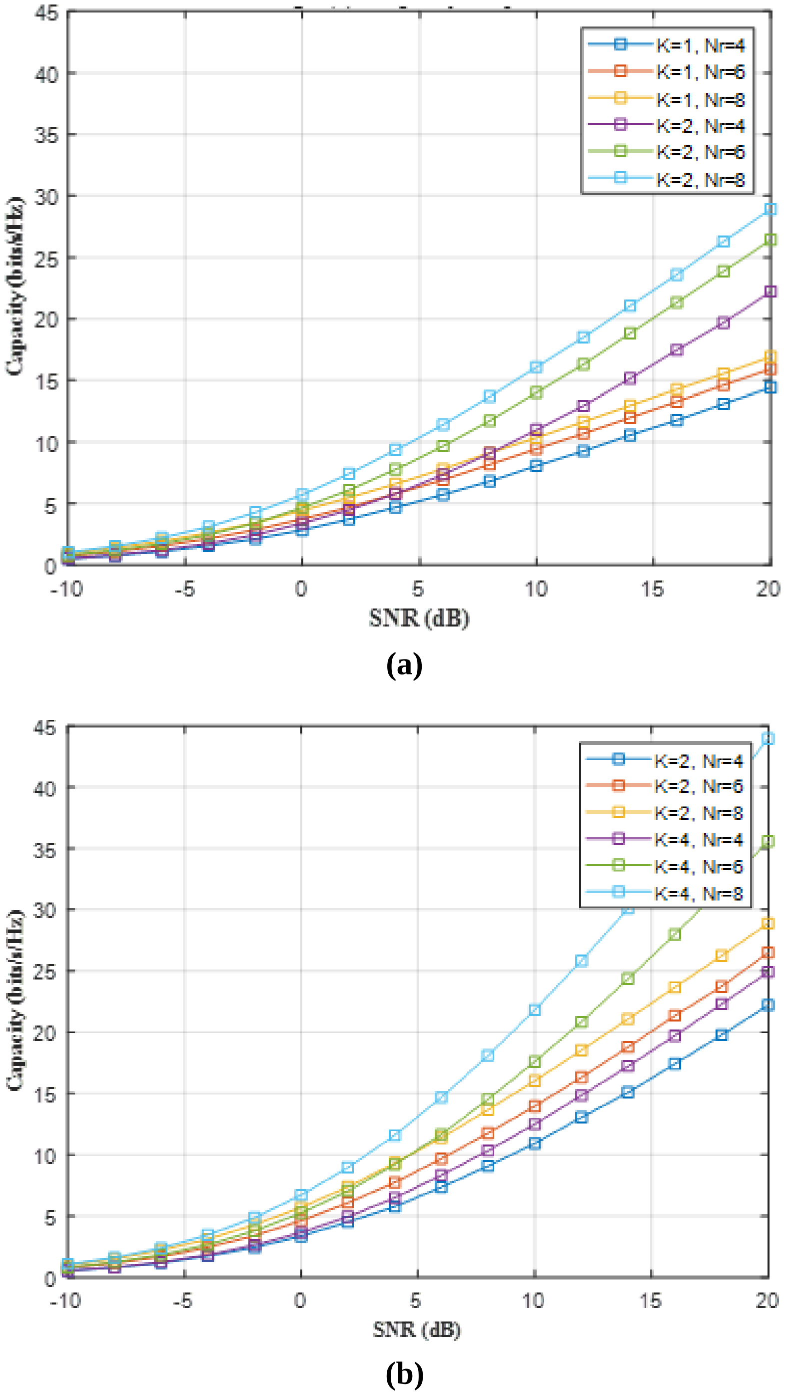
TABLE II. SAMPLE BER VALUES FOR DIFFERENT CONFIGURATIONS.

SNR (dB)	**K = 1, Nr = 4**	**K = 2, Nr = 6**	**K = 4, Nr = 8**
−10	0.32	0.38	0.14
0	0.07	0.06	0.0008
10	0.0018	0.0007	1e-05
20	0.00006	2e-05	0.0

As SNR and the number of receive antennas increase, BER significantly decreases. For instance, the BER for K = 4 and Nr = 8 drops to nearly zero at 10 dB, showing strong robustness in high-density multi-user environments.

Fig. 3 shows the ergodic channel capacity performance across F setups. In Fig. 3(a), the capacity for K = 1 and 2 users is plotted for multiple Nr values. It is evident that higher Nr leads to greater capacity due to spatial multiplexing and diversity. For instance, with K = 2 and Nr = 8, the capacity at 10 dB reaches over 30 bps/Hz. Fig. 3(b) depicts the capacity for K

= 2 and 4 users. As more users are added, the total capacity still increases, but with diminishing per-user efficiency due to interference and power sharing.



(a)

(b)

Fig. 3. Capacity vs. SNR with STBC and regularized ZF equalization: (a) K = 1, 2 user, Nr = 4, 6, 8 (b) K = 2, 4 user, Nr = 4, 6, 8.

To support these findings, Table III summarizes capacity values for selected SNRs. The data confirms that the system exhibits strong spectral efficiency, achieving over 43 bps/Hz at 20 dB with K = 4 and Nr = 8. This highlights the scalability and throughput potential of the proposed architecture.

TABLE III. SAMPLE ERGODIC CHANNEL CAPACITY VALUES (BPS/HZ).

SNR (dB)	K = 1, Nr = 4	K = 2, Nr = 6	K = 4, Nr = 8
−10	1.2	3.6	6.2
0	5.4	13.7	21.3
10	13.9	25.1	34.6
20	22.5	36.9	43.2

Capacity increases steadily with higher SNR and more receive antennas. The configuration with K = 4 users and Nr = 8 antennas achieves over 43 bps/Hz at 20 dB, confirming the system's efficiency and suitability for massive multi-user uplink scenarios in future networks.

In summary, both the numerical data and graphical results demonstrate the robustness, efficiency, and scalability of the proposed MU-MIMO system using STBC and regularized ZF equalization. The architecture achieves excellent performance in both low and high SNR regimes while maintaining low complexity at the receiver.

7. CONCLUSION

The performance of an uplink MU-MIMO wireless system with QPSK modulation, Alamouti space-time block coding (STBC) and regularized ZF equalizer was studied in this paper. Simulations results indicate that BER and channel capacity are enhanced with the growth of number of receive antennas. The regularization term improves numerical stability so that reliable detection is guaranteed even over bad channels. The proposed approach provides a low-complexity and flexible solution applicable to multi-user communication in the forthcoming 5G and 6G networks. In addition to curve-based analysis, numerical results presented in tables further confirmed the improvements in error rates and spectral efficiency. The system consistently demonstrated robust performance under varying user loads and SNR levels.

References

[1] M. M. Kamruzzaman, W. He, and X. Peng, “Performance of multiuser MIMO uplink wireless communication using space time block coding for Rayleigh fading channel,” in Proc. 17th Int. Conf. Computer and Information Technology (ICCIT), Shenzhen, China, 2014, pp. 462–465.

[2] J. Zhu, L. Xiao, P. Xiao, A. Quddus, C. He, and L. Lu, “Differential STBC-SM scheme for uplink multi-user massive MIMO communications: System design and performance analysis,” IEEE Trans. Veh. Technol., vol. 69, no. 7, pp. 7733–7747, Jul. 2020.

[3] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, “Cell-free massive MIMO versus small cells,” IEEE Trans. Wireless Commun., vol. 16, no. 3, pp. 1834–1850, Mar. 2017.

[4] Sana Abdaljlil, Fursan Thabit and Amer Zerek, “A Comparison Study of BER Performance for 8-PSK and 8-QAM Trellis Coded Modulations in a 2x2 OSTBC-MIMO System”, IEEE 11th International Conference on Systems and Control (ICSC).December 18-20 ,2023,Sousse, Tunisia.

[5] S. Chen, S. Sun, and Q. Gao, “A survey of user-centric 5G cellular networks,” IEEE Commun. Mag., vol. 56, no. 10, pp. 110–117, Oct. 2018.

[6] M. Abdel-Aziz, K. M. Rabie, and B. Adebisi, “Performance of MIMO with STBC under channel aging,” IEEE Access, vol. 7, pp. 78494–78505, 2019.

[7] T. L. Marzetta, “Massive MIMO: An introduction,” Bell Labs Tech. J., vol. 20, no. 1, pp. 11–22, 2016.

[8] B. Makki, T. Svensson, and M. Zorzi, “Zero-forcing (ZF) detection in massive MIMO systems,” IEEE Wireless Commun. Lett., vol. 6, no. 3, pp. 310–313, Jun. 2017.

[9] Sana Ahmed Abdaljlil, HOSAM ALMQADIM , Amer Ragab Zerek and Olga Boiprav , “ Performance Analysis of BER for OSTBC-MIMO System Concatenated with QPSK-TCM Over Different Wireless Channels” 2022 IEEE 21st international Ccnference on Sciences and Techniques of Automatic Control and Computer Engineering (STA) , December 19-21, 2022, Sousse-Tunisia, 2022.

[10] S. Han, C. L. I, Z. Xu, and C. Rowell, “Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G,” IEEE Commun. Mag., vol. 53, no. 1, pp. 186–194, Jan. 2015.

[11] M. Agiwal, A. Roy, and N. Saxena, “Next generation 5G wireless networks: A comprehensive survey,” IEEE Commun. Surveys Tuts., vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[12] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath Jr., “Channel estimation and hybrid precoding for millimeter wave cellular systems,” IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 831–846, Oct. 2014

[13] A. S. Kharwat,"Precoded Spatial Multiplexing MIMO Systems in Time- Varying Fading Channel," Journal of Communications, vol. 9, no. 2, pp. 118--125, 2014