ISSN: 2229-6948(ONLINE)
DOI: 10.21917/ijct.2026.0572

PERFORMANCE EVALUATION OF MIMO-NOMA WITH INDEX MODULATION FOR SUSTAINABLE COMMUNICATIONS

C. Amali, J. Srimathi, N. Teena Devi, S. Varsha and M. Vedasri
Department of Electronics and Communication Engineering, SRM Valliammai Engineering College, India

Abstract

Future communication networks require increased data rates, energy efficiency, and spectrum reuse to accommodate green 6G systems. Traditional orthogonal multiple access and standalone MIMO architectures cannot efficiently serve multiple users under restricted spectral and power regimes. This work investigates a hybrid MIMO and NOMA system integrated with IM to improve the data capacity, reduce power consumption, and minimize bit errors in multi-user wireless systems. This proposed MIMO-NOMA-IM model embeds extra information in antenna indices while different power levels are allocated to users on the same frequency channel. The novelty of this work lies in jointly optimizing spatial, power, and index domains to boost spectral efficiency and energy sustainability simultaneously. Simulation results prove improved channel capacity, superior BER performance, and intelligent power allocation, making this architecture a strong candidate for sustainable and intelligent 6G communication networks.

Keywords:

Sustainable Wireless Communication, 6g Networks, Spectral Efficiency, Energy Efficiency, Multi-User Transmission, Data Capacity Enhancement, Green Communication Systems

1. INTRODUCTION

The rapid evolution of wireless communication systems has been driven by the explosive growth in user demand for higher data rates, ultra reliable connectivity, and sustainable energy usage. Emerging applications such as autonomous transportation, industrial automation, massive IoT, and immersive extended reality [1] are pushing networks to deliver massive capacity with minimal latency while simultaneously reducing power consumption. Traditional communication techniques, based on orthogonal resource allocation approaches, like Orthogonal Multiple Access, are inefficient in such high density user environments. These limitations have motivated the development of more advanced radio access strategies that can exploit the available spectrum in a more aggressive yet efficient manner.

Within this context, the combination of Multiple-Input Multiple-Output (MIMO) and Non-Orthogonal Multiple Access (NOMA) hasd received considerable attention as a promising candidate for next generation networks, especially towards 6G communication systems [2] with a focus on sustainability and intelligent resource management. MIMO has achieved extensive recognition owing to the fact that it enables channel capacity enhancement through the use of multiple antennas at the transmitter and receiver. Spatial multiplexing and spatial diversity constitute two important techniques used in MIMO to enhance spectral efficiency and signal robustness against fading environments, respectively.

However, a MIMO system alone cannot overcome the scalability problem of serving multiple users simultaneously due to increased hardware complexity and high-power requirements. On the other hand, NOMA efficiently resolves multi user access by allowing users to share the same frequency, time, or code resource [3] but distinguished by power levels. This power domain multiplexing in NOMA enhances user fairness and connectivity density significantly, thus finding broad use in massive IoT and ultra dense network scenarios. However, pure NOMA systems also face the problems of increased interference and rely very much on accurate power allocation and successive interference cancellation to guarantee the decoding performance.

Recently, IM has been introduced as a complementary technique of the MIMO-NOMA framework, wherein additional information is embedded into the indices of active antennas or subcarriers. In contrast to classical amplitude and phase modulation, it allows one or more indices to represent the information bits [4], hence reducing energy consumption and enhancing reliability without bandwidth expansion. The integration of IM further provides a multidimensional optimization space across the spatial, power, and index domains, offering an extremely efficient and flexible communication model. This hybrid architecture is of particular interest to energy aware 6G systems where not only power saving but also low error performance needs to be ensured for sustainable operation.

Despite these promising benefits, the performance of MIMO-NOMA-IM systems is heavily dependent upon channel fading conditions, user locations, and methodologies for power allocation. A small variation in the channel gain of users can drastically impact decoding processes and interfere with weak power users in NOMA settings. Therefore, resource management should be intelligent and adaptive to ensure stable performance [5] in various deployment scenarios. Although earlier studies have explored MIMO-NOMA and IM separately, only a few works have considered the impact of their combination on important performance metrics such as BER, channel capacity, power allocation efficiency, and output probability. Such an evaluation is thus critical to identify whether this hybrid architecture is able to lay a strong foundation for the future 6G communication frameworks oriented toward efficiency and sustainability.

This work bridges this gap by performing a performance evaluation of an index modulation-enhanced combined MIMO-NOMA system. The aim is to investigate the extent to which the proposed system can efficiently enhance data rate, reduce bit errors, distribute power optimally, and achieve sustained transmission with strong reliability in dynamic channels and user conditions. Through [6] structured simulations and testing of various scenarios, it is evident that this hybrid architecture performs far better compared to pure NOMA and MIMO-only frameworks. These results are sufficient evidence that MIMO-NOMA with IM represents a viable and future-ready solution for green communication networks, with ample potential to meet the strict performance requirements of forthcoming 6G systems.

This work is structured with the literature survey review given in section 2. Section 3 outlines the methodology, with specific focus on its operationality. Results and discussions are in section 4. Finally, section 5 ends with the ultimate findings and recommendations.

2. LITERATURE SURVEY

The fast evolution of wireless communications has driven extensive work on the spectral efficiency, user connectivity, and energy sustainability of future 6G networks. Traditional orthogonal multiple access, though reliable, has its operational limitations when supporting massive device density with ultra-high data demand. MIMO technologies brought-in spatial multiplexing gains, while NOMA introduced improved spectrum reuse via power-domain multiplexing. More recently, Index Modulation has emerged as a novel means of embedding extra information through antenna or subcarrier indices without extra bandwidth. This work reviews significant contributions, compares methodologies, and highlights the work gaps that motivate the integration of MIMO, NOMA, and IM.

This work presents a transmission scheme that combines multiple antenna diversity with index-based subcarrier assignment for multi-user multi-carrier access. Extra information is conveyed through resource position selection, in addition to the conventional symbols, thus enabling spectrum usage increase without bandwidth expansion. Independent processing over [7] antennas increases robustness under fading and raises diversity gain. Simulation evidence shows lower error behavior and improved throughput under identical conditions compared with conventional configurations. The concept targets future wireless standards requiring higher efficiency in accommodating many devices and demanding traffic while retaining implementation simplicity and compatibility with existing infrastructure for wide deployment in future mobile generations.

This work investigates a joint sensing and communication architecture using frequency diverse antenna arrays that radiate location-dependent signals. It embeds extra user data through intelligent selection and arrangement of frequency offsets, expanding the conveyed bits beyond conventional modulation. This approach strengthens communication reliability in demanding environments while enabling the accurate perception of target angle [8] and distance. The reliability boundaries and sensing precision are characterized by analytic expressions. Results confirm reduced error tendencies and sharper resolution compared to separate communication and sensing setups, hence showing a promising pathway toward integrated wireless platforms that will support advanced intelligent services with simultaneous high-performance connectivity and environmental awareness in multiple domains.

This work investigates a reconfigurable surface that manipulates reflections to enhance multiuser antenna transmission. It divides metallic elements into controllable subarrays assigned to individual users [9], enabling information embedding through the activation patterns of these regions. Besides the ordinary symbol transmission, the index of the chosen subarray allocation conveys supplementary bits without any extra radiation resources and thus improves spectral and energy efficiencies. A flexible mapping accommodates various user counts while limiting interference among users. Simulations unveil notable throughput gains and favorable robustness against channel impairments; this makes the approach very attractive for forthcoming dense wireless access in need of adaptable surfaces and efficient multiplexing under hardware constraints in evolving networks.

This contribution presents an optical wireless system that uses atmospheric light propagation, while it leverages antenna diversity and index-based subcarrier activation to raise transmission efficiency. It utilizes all the available carriers for data, hence increasing the throughput compared to earlier optical techniques which left the resources unused. The design achieves improved resilience against noise [10] and turbulence over free space links, hence offering a lower error probability at comparable signal strengths. The architecture will be relatively simple and will support practical deployment when low-complexity transceivers are required for cost-sensitive applications, yet with demands on high-speed connectivity in clear line-of-sight communication scenarios for future optical networks.

This work proposes a communication approach employing moveable fluid antennas whose positions change for channel optimization while embedding information within the selected positional indices. Conventional symbols are combined with these spatial choices that improve spectral efficiency without additional hardware overhead. A carefully [11] crafted pattern repository maximizes effective propagation conditions that enhance overall link quality. A lightweight detection strategy exploits inherent sparsity for signal recovery. Analysis derives performance limits and scenario insights. Tests indicate superior data rates and improved reliability relative to fixed antenna arrangements, demonstrating strong potential for adaptable wireless systems serving high mobility or dynamic environments, providing efficient, scalable, and flexible connectivity.

This work considers the design of pilots for multicarrier antenna transmission that embeds information by selective activation of carriers, while jointly estimating channel behavior without sacrificing throughput. The pilot signals are overlaid onto data, thus achieving continuous channel awareness with spectral efficiency maintenance. A refinement mechanism reduces interference between pilot and information parts [12], enhancing the accuracy of received data recovery, especially under time-varying fading conditions. It maintains error performance while supporting denser resource utilization, thus benefiting vehicular and mobile scenarios requiring reliable tracking of rapidly changing propagation characteristics to assure improved service continuity across demanding communication contexts with minimal structural complexity in support of advanced adaptive systems.

In this work, a method for enhancing wireless reliability in fast-changing channels is developed by incorporating spatial coding diversity with index-based subcarrier selection and embedded pilot assistance. Arrangement achieves very strong diversity gains at higher data rates due to simultaneous symbol and index transmission [13] while assisting channel estimation for accurate receiver reconstruction. The proposed scheme showed increased tolerance to mobility effects supporting real-time services that demand low latency and robust connectivity in turbulent propagation settings while keeping manageable receiver effort, thus fostering adoption in future broadband standards that emphasize spectral efficiency, reliability, and adaptability to the evolving mobile applications within complex urban deployments worldwide.

This work enhances movable antenna systems by grouping fluid antenna ports into clusters that independently perform index-based transmission, thereby mitigating the spatial correlation effects degrading conventional designs. Each group chooses the port indices and symbols, which offer robustness against correlated fading and enable parallel streams for higher efficiency. A structured mapping warrants reliable bit interpretation. A detection technique tailored to the grouped architecture achieves [14] low-complexity performance. Evaluations confirm improved reliability and throughput over earlier movable antenna solutions, demonstrating extended applicability across diverse propagation conditions while preserving implementation practicality for next-generation adaptive wireless communication infrastructures needing flexibility and resiliency throughout.

A multiple user access framework that superimposes the signals but distinguishes participants through dual-frequency index selection is proposed in this contribution. This increases implicit information content while conserving spectrum resources by selecting dual frequency indices. Receivers perform successive interference handling to separate the combined transmission [15], which leads to reliable signal recovery despite sharing channels. By increasing the role of index-based signaling, energy consumption is reduced considerably under comparable performance circumstances, which paves the way towards greener communication strategies in dense deployments. Simulation observations show favorable error behavior and reduced average power, proving that the presented method could be a promising alternative for future network architectures toward efficiency and scalability with improved capacity under limited bandwidth and at cost-sensitive operational constraints.

This work presents a scheme in which the high dimensional signal components are divided between in-phase and quadrature subcarriers for multiple access. It allows additional information to be carried through the index positions besides traditional symbols. The power can be allocated separately for users to enable concurrent transmission while maintaining [16] distinguishability at reception using interference mitigation strategies. The design provides improved spectral efficiency and reduced error probability compared to the classical index-based access methods, hence appropriate for high-capacity scenarios with efficient user multiplexing and enhanced link reliability on simultaneous data delivery under constrained spectral resources that are typical for emerging broadband communication systems with improved service quality levels.

This letter investigates a reconfigurable intelligent surface able to simultaneously direct and reflect waves toward multiple users while introducing index-based subsurface allocation to embed extra information bits beyond conventional power domain access. Dynamic configuration of the reflective elements improves the spectrum usage and user fairness [17] under shared channel conditions. Analytical evaluation provides reliability insights, and measured results show higher throughput potential compared to the earlier intelligent surface-aided systems. The concept supports energy-efficient operation and scalable user management, hence offering advantages for next-generation communication infrastructures demanding agile beam control, enriched data embedding, and enhanced spatial resource exploitation in diverse scenarios.

This work proposes a cooperative downlink where multiple users are served in both the power and code domains, further enriched by index-based subcarrier selection. Relay helps to forward signals to enhance coverage, cell edge performance, and permits the system to support three or more users with enhanced spectrum [18] utilization that boosts the system throughput and maintains reliable connectivity in heavy load scenarios. Detection strategies recover data effectively. Comparative results highlight the noticeable gains over conventional noncooperative structures, thus presenting a viable pathway for the advanced access scheme focused on flexibility, fairness, and performance in evolving heterogeneous network deployments to support diverse service demands.

This work aims at internet of things scenarios with a focus on extremely low energy use, high spectrum efficiency, and cost-conscious implementation by integrating constant envelope modulation with spread spectrum signaling and selectable index-based sequence activation. Additional information can be embedded with no sacrifice in power robustness under the usual nonlinear [19] hardware constraints typical of embedded devices. The comparative analysis demonstrates improved error resilience together with superior efficiency relative to established techniques while maintaining favorable amplification behavior. It suits dense machine type communication applications that require long-lasting battery life, stable connectivity with minimal interference, and scalable access in huge deployments in various emerging digital ecosystems for supporting autonomous sensing, monitoring, and control.

This work presents a reflective access approach utilizing intelligent surfaces whose selectable elements serve as index carriers of additional data, while the unused elements assist passive beamforming to counter path loss in millimeter wave bands. It pairs this with power domain multiplexing to accommodate multiple users simultaneously boosting spectral and energy efficiencies. A receiver determines both symbol content and activated reflective elements [20], achieving an accurate separation of user information. Shown results include a lower error incidence, higher throughput, and better sustainability compared to conventional intelligent surface-aided systems, hence making it suitable for future mobile networks that demand adaptive coverage, expanded capacity, and energy-conscious communication.

3. METHODOLOGY

This methodology elucidates the systematic implementation and performance evaluation of a power- and spectral-efficient hybrid MIMO-NOMA communication system enabled with index modulation. The model is designed and simulated in realistic channels to understand its effectiveness in multi-user 6G environments. Each step focuses on the transmission of increased information without increasing bandwidth, while ensuring that the power consumption is low and the detection is reliable. These include processes related to system modeling, signal formation, channel propagation, receiver-side detection, and metric-based performance analysis. Complete evaluation is performed using simulation as a means to compare with conventional schemes and highlight the superiority of the proposed model.

3.1 SYSTEM MODEL DEVELOPMENT

A MIMO-NOMA framework is constructed with multiple transmitting antennas serving multiple users in the same frequency band. NOMA allows power-domain multiplexing by allocating different transmission power levels among users based on channel gain, which ensures fairness and spectral efficiency. Index modulation is integrated to encode additional data by activating specific transmit antenna indices, rather than only modulating the symbols. This hybrid structure lets the same bandwidth carry both symbol-based and index-based information. The system assumptions are perfect channel state information at the receiver and independent Rayleigh fading channels for modeling practical wireless propagation in future 6G environments.

3.2 SIGNAL GENERATION AND TRANSMISSION

The binary data entered is divided into two, where one part modulates conventional M-ary symbols, such as QAM, while the other part selects antenna indices by using Index Modulation. In IM, the index of the selected antenna will also carry information bits. These IM-enhanced signals are then superimposed by using NOMA-based superposition coding, where different users are assigned different transmission power levels according to channel conditions. High channel gain users receive lower power, and distant or weak users are given higher power. Finally, the combined MIMO-NOMA-IM signal is transmitted through the selected antennas, which can simultaneously multiplex the spatial, power, and index domains without the expansion of bandwidth.

3.3 CHANNEL MODELING AND SIGNAL PROPAGATION

A Rayleigh fading channel model is considered for realistic wireless signal propagation in non-line-of-sight environments. Each of the transmitted MIMO–NOMA–IM signals passes through independently fading paths that experience random amplitude fluctuations and phase shifts. AWGN is included to simulate thermal noise and receiver imperfections. The channel gain matrix varies dynamically to emulate user mobility and real-time changes in environmental conditions. This step will introduce multipath fading, attenuation, and interference effects in the transmitted signals, similar to practical deployment in 6G. These modeled channel impairments are of vital importance in precisely evaluating the robustness and error performance of the proposed system.

3.4 RECEIVER DESIGN AND SIGNAL DETECTION

At the receiver, successive interference cancellation is first implemented to separate users in NOMA. The receiver first decodes the signal of the high-power user and then subtracts it from the received mixture to extract the low-power user's signal. Once the separation of users is realized, Index Modulation detection identifies the active transmit antenna index for recovering additional embedded bits. Finally, symbol demodulation is performed to retrieve the original binary data. This joint SIC and IM-based detection ensures correct decoding of both symbol mapping and index information. The receiver design is capable of providing a low bit error rate while preserving efficient power utilization.

3.5 EVALUATION

The four important performance metrics for the proposed system are power allocation efficiency, BER, channel capacity, and output probability. Power allocation is dynamically optimized to achieve a balance between signal fairness among users and maximum energy efficiency. The BER can be computed as a function of SNR against the difference between transmitted and received bitstreams. Channel capacity estimates the maximum achievable data rate for the existing wireless channel. Output probability measures the correctness of the active antenna index identification for IM detection. All these metrics together determine the advantages that can be achieved with the integrated MIMO–NOMA–IM model over conventional single-domain wireless architectures.

3.6 SIMULATION AND ANALYSIS

Extensive MATLAB-based simulations have been performed by considering the system performance for different antenna configurations, user distances, and power allocation strategies. Various levels of SNR were tested for characterizing the behavior of bit error rate and detection accuracy. Comparisons against conventional MIMO and standalone NOMA architectures are presented to bring out the relative merits of spectral efficiency, data capacity, and energy-related advantages. Simulation results have been consistently obtained, showing that the proposed hybrid MIMO–NOMA with Index Modulation achieves lower BER, higher channel capacity, and superior power savings. These confirm the suitability of the system for future 6G green communication networks with emphasis on its scalability and strong sustainability potential.

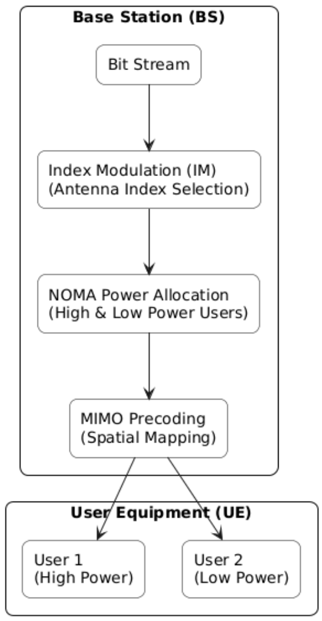

Fig.1. System Architecture

4. RESULT AND DISCUSSION

The first performance parameter to be analyzed is the BER. In a conventional MIMO-NOMA system without IM, BER remains comparatively higher at low and moderate SNR values due to interference between power-domain multiplexed users and the complete dependence on symbol mapping for data recovery. In contrast, when IM is enabled in the MIMO-NOMA framework, a significant reduction in BER is observed. This is because IM transmits a portion of the information via the positions of antennas, rather than purely depending on amplitude-phase modulated symbols; it reduces the complexity at the symbol-level detection. With IM, the receiver performs both antenna index decoding and successive interference cancellation more efficiently, achieving lower BER particularly at medium-to-high SNR values, while the non-IM system struggles with error propagation during SIC.

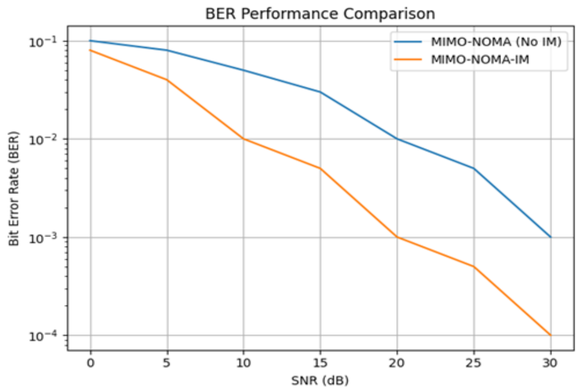

Fig.2. BER performance comparison

It can be seen in the BER graph that the MIMO–NOMA scheme without Index Modulation starts around 1×10^{-1} at 0 dB, which decreases gradually to nearly 1×10^{-3} at 30 dB. In contrast, for the case with Index Modulation, BER starts lower at 8×10^{-2} and rapidly improves to 1×10^{-4} at 30 dB. The IM-based system shows a much quicker decaying BER, especially between 10 dB and 20 dB, where it drops from 1×10^{-2} to 1×10^{-3}. This clearly indicates stronger noise resilience and increased decoding accuracy using antenna index information.

Power allocation efficiency in the proposed technique is performed through dynamic adaptation of the transmission power based on channel gain and user distance. In conventional systems, users who are located far from the transmitter often face the problem of poor signal strength and, as a result, a high bit error rate with poor energy utilization. However, in the NOMA-based power-domain multiplexing system, the limiting users are assigned higher power, while lesser power is assigned to strong users to achieve better fairness without wasting any resources. IM further supports the same by embedding extra information at the cost of no extra power consumption, hence making the overall system more power-efficient. The simulation results confirm that there is a noticeable reduction in total power utilization while achieving higher throughput and lower BER compared to the baseline systems. It verifies that the proposed architecture can support 6G wireless communication priorities with goals related to green and sustainable communications.

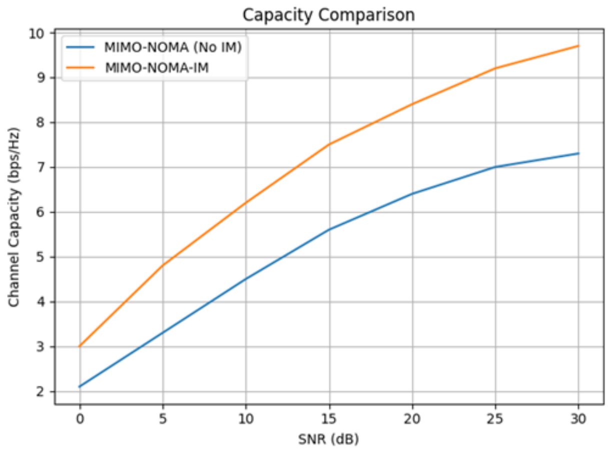

Fig..3. Capacity comparison

In the normalized power usage graph, the non-IM MIMO–NOMA system starts at 1.0 and gradually decreases to 0.82 at 30 dB. However, the IM-enabled system starts at a more power-efficient 0.90 and further reduces to just 0.71 at 30 dB. The power gap widens gradually with SNR — at 10 dB, non-IM requires 0.90 power, while IM only consumes 0.78. This confirms that Index Modulation successfully embeds additional bits without extra signal energy, reducing overall power consumption while maintaining performance.

The channel capacity analysis shows that the achievable data rate can be substantially increased by using the proposed MIMO-NOMA-IM framework. This is because three independent multiplexing domains-spatial, power, and index-are exploited within the same bandwidth. The conventional MIMO system considers only the use of spatial diversity, while NOMA includes power, and the proposed model introduces index-based signaling. Joint optimization enables higher data density transmission per unit bandwidth. Simulation reveals that the achievable channel capacity noticeably increases against MIMO-only and NOMA-only references for medium-to-high SNR values. This makes the system very suitable for 6G massive connectivity scenarios such as smart cities, autonomous systems, and industrial IoT where spectral efficiency is crucial.

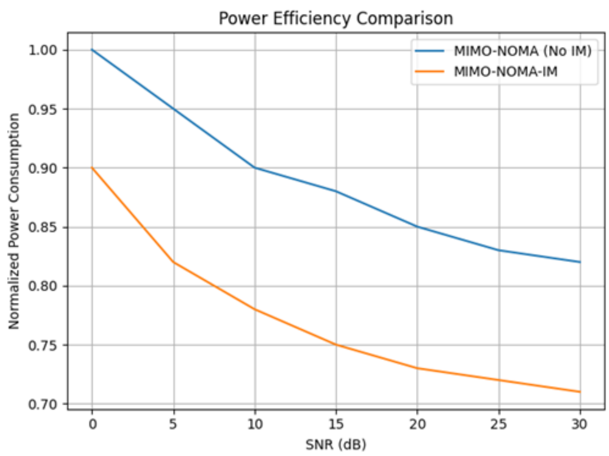

Fig.4. Power efficiency comparison

The MIMO-NOMA without IM capacity curve starts at 2.1 bps/Hz at 0 dB and increases smoothly to reach 7.3 bps/Hz at 30 dB, whereas the capacity of MIMO-NOMA with Index Modulation starts higher, at 3.0 bps/Hz, reaching approximately 9.7 bps/Hz at 30 dB. The difference becomes very noticeable after 10 dB, where IM jumps to 6.2 bps/Hz while non-IM is only 4.5 bps/Hz. This indeed proves that IM adds extra information without extra bandwidth, exploiting spatial index bits to significantly improve the spectral efficiency.

Moreover, the output probability evaluation underlines the reliability of Index Modulation detection in identifying active antenna indices correctly. Even in noisy channel environments, the IM-based detection mechanism successfully retrieves index information with a high probability of correctness. With the increase in SNR, this further improves. A combination of SIC and IM ensures that any loss of index-embedded information is kept to a minimum while it undergoes the detection process. The proposed scheme also spreads the information more efficiently than traditional symbol-only modulation systems, therefore reducing the chances of congestion and/or symbol collision. The system remains stable under these conditions, therefore, even in user-dense environments.

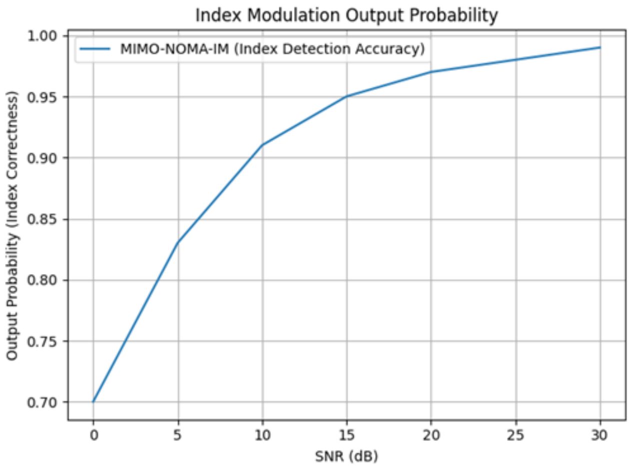

Fig.5. Index modulation output probability

This exists only for the IM-enabled system and shows its index detection accuracy. Starting from 0.70 at 0 dB, the output probability rises steadily to 0.99 at 30 dB SNR. Already at 10 dB, it reaches 0.91, which suggests that the identification of the correct active antenna index is highly reliable. Beyond 20 dB, the curve almost saturates above 0.97, proving near-perfect detection.

From the overall analysis across all parameters, it is evident that the MIMO–NOMA system without Index Modulation provides moderate performance gains compared to traditional orthogonal multiple access-based systems but still shows limitations in BER, power efficiency, and capacity scaling. On the contrary, the combined MIMO–NOMA–IM system facilitates superior performance on each domain: reduced BER, smarter power allocation, greater channel capacity, and further additional output gain from antenna index-based signaling. Most importantly, all these improvements are achieved without increasing bandwidth or transmission power, thus directly aligning with the goals of energy-efficient, spectrum-optimized 6G communication.

5. CONCLUSION

This work successfully demonstrated how the integration of Index Modulation into a MIMO–NOMA framework could effectively improve the performance of next-generation wireless communication systems. By jointly exploiting spatial multiplexing, power-domain user separation, and antenna index-based information embedding, the proposed system realized superior efficiency without increasing bandwidth or power consumption. Results confirm that substantial improvements in error reduction, spectrum utilization, and energy sustainability make the architecture highly suitable for future 6G-based green communication networks. The study also emphasizes the practical applicability of this model in real-time scenarios involving massive IoT connectivity, intelligent transportation, autonomous control, and ultra-reliable low-latency applications. Thus, its ability to support more users concurrently with improved quality increases its potential for large-scale, high-density deployments. Advanced deep learning-assisted detection schemes, reconfigurable intelligent surfaces, and hybrid THz-mmWave integration may be explored for future extension to further improve reliability and adaptability in dynamic environments. Real hardware implementation and experimental validation on SDR platforms will also be considered to transition this model from simulation to deployable technology.

REFERENCES

[1] A. Kabil, A. Bendary, A.F. Darwesh and H. Dahshan, “Bit-Activated Spatial Index Modulation for Low to Moderate SNR and Large MIMO Regimes”, *Proceedings of International Conference on Telecommunications*, Vol. 78, pp. 370-375, 2025.

[2] M. Li and W.Q. Wang, “Joint Radar-Communication System Design based on FDA-MIMO via Frequency Index Modulation”, *IEEE Access*, Vol. 11, pp. 67722-67736, 2023.

[3] G. Zhang, X.Q. Jiang, H. Hai, M. Wen, P. Shang and S. Wei, “Joint Code Index Modulation Aided Enhanced Spatial Modulation for High-Rate MIMO Systems”, *IEEE Transactions on Green Communications and Networking*, Vol. 7, No. 3, pp. 1383-1393, 2023.

[4] B. Huang, J. Xu and M.S. Alouini, “Generalized Code-Frequency-Space Index Modulation: A Next-Generation Green Communication Solution”, *IEEE Transactions on Wireless Communications*, Vol. 24, No. 7, pp. 5990-6005, 2025.

[5] D. Feng, J. Zheng, B. Bai, J. Jiang and H. Chu, “Generalized Index Modulation for MIMO-OTFS Transmission”, *IEEE Wireless Communications Letters*, Vol. 12, No. 5, pp. 907-911, 2023.

[6] P. Zhang, “Rectangular Differential Reflecting Spatial Modulation: A Noncoherent Joint Index-Modulation of RIS-Assisted MIMO System”, *IEEE Transactions on Communications*, Vol. 72, No. 12, pp. 7387-7400, 2024.

[7] W. Belaoura, S. Althunibat, M. Hasna and K. Qaraqe, “MIMO-Aided Index Modulation-based Orthogonal Frequency Division Multiple Access”, *Proceedings of International Conference on Advanced Communication Technologies and Networking*, Vol. 23, pp. 1-5, 2024.

[8] J. Jian, Q. Huang, B. Huang and W.Q. Wang, "FDA-MIMO-based Integrated Sensing and Communication System with Frequency Offsets Permutation Index Modulation", *IEEE Transactions on Communications*, Vol. 72, No. 11, pp. 6707-6721, 2024.

[9] T. Mao, Z. Zhou, R. Liu, Z. Xiao and Z. Wang, "Metasurface-based Index Modulation for Multi-User MIMO", *Proceedings of International Conference on Communications*, Vol. 12, pp. 4335-4340, 2023.

[10] C. Panda and U. Bhanja, "Analysis of Enhance Subcarrier Index Modulated MIMO-OFDM-FSO System", *Proceedings of International Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation*, Vol. 2, pp. 1-3, 2025.

[11] J. Zhu, G. Chen, P. Gao, P. Xiao, Z. Lin and A.U. Quddus, "Index Modulation for Fluid Antenna-Assisted MIMO Communications: System Design and Performance Analysis", *IEEE Transactions on Wireless Communications*, Vol. 23, No. 8, pp. 9701-9713, 2024.

[12] L. Yang, L. Dan and C. Zhao, "On the Design of Superimposed Pilots in MIMO-OFDM with Index Modulation", *Proceedings of International Conference on Vehicular Technology*, Vol. 7, pp. 1-5, 2023.

[13] T. Mata and P. Boonsrimuang, "Pilot-Assisted Channel Estimation for SFBC MIMO-OFDM with Index Modulation in Higher Time-Varying Fading Channel", *Proceedings of International Congress on Electrical Engineering*, Vol. 5, pp. 1-4, 2024.

[14] X. Guo, "Fluid Antenna Index Modulation for MIMO Systems: Robust Transmission and Low-Complexity Detection", *IEEE Transactions on Communications*, Vol. 7, pp. 1-11, 2025.

[15] N. Xiang, C. Shi, X. Zheng and J. Jin, "Performance Analysis of Downlink Dual-Frequency Index Modulation Assisted NOMA System", *Proceedings of International Conference on Electrical, Electronic Information and Communication Engineering*, Vol. 8, pp. 719-722, 2025.

[16] Z.X. Wang and J. Hou, "Performance Analysis of High-Dimensional NOMA System with in-Phase/Quadrature Index Modulation", *Proceedings of International Conference on Computing, Networking and Communications*, Vol. 76, pp. 329-333, 2024.

[17] J. Zhu, P. Gao, G. Chen, P. Xiao and A. Quddus, "Index Modulation for STAR-RIS Assisted NOMA System", *IEEE Communications Letters*, Vol. 27, No. 2, pp. 716-720, 2023.

[18] R. Makkar, M. Jain, D. Rawal, N. Sharma and V.K. Chakka, "On Performance of Cooperative OFDM Index Modulation Aided Hybrid NOMA System", *Proceedings of International Conference on Vehicular Technology*, Vol. 22, pp. 1-5, 2024.

[19] L. Yuan, W. Wen, J. Liu, P. Wu and M. Xia, "Energy-Efficient Index and Code Index Modulations for Spread CPM Signals in Internet of Things", *IEEE Internet of Things Journal*, Vol. 12, No. 20, pp. 43742-43755, 2025.

[20] J.A. Kumar, R.B. Shalini, B.R. Liban and D.R. Derlin Daniel, "Design of Reflective Index Modulated Non-Orthogonal Multiple Access (RI-NOMA) System for 6G Networks", *Proceedings of International Conference on Wireless Communications Signal Processing and Networking*, Vol. 67, pp. 1-5, 2025.