Systematic Review of VLC-Based NOMA Using Machine Learning Algorithms

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Abstract

Visible light communication (VLC) integrated with nonorthogonal multiple access (NOMA) is a promising technique to meet the increasing demand for high capacity, energy-efficient communication in forthcoming 6G networks. This work thoroughly evaluates VLC-NOMA systems and emphasizes the incorporation of machine learning (ML) approaches to improve spectrum efficiency, the bit error rate, and resource allocation. A technique based on Preferred Reporting Items for Systematic Reviews and Meta-analyses produced 244 records, among which 45 were selected for comprehensive study. The review identified obstacles, including scalability, computational complexity, and insufficient experimental validation. A comparative examination elucidated the strengths and limits of machine learning methodologies, including machine learning, deep neural networks, and federated learning, in addressing these difficulties. The study identified key research gaps, proposed future directions, and emphasized the need for hybrid optimization techniques, lightweight machine learning models, and real-world implementations. The findings contribute to the development of robust, scalable VLC-NOMA systems for 6G applications.

Keywords: Visible Light Communication; Nonorthogonal Multiple Access; Machine Learning; Artificial Intelligence; 6G; Resource Management; Deep Learning

1. Introduction

Rapid advancements in communication technologies have driven the development of next-generation networks, particularly the forthcoming sixth generation (6G) [1]. With the global society becoming more connected than before, the demand for high-order data rates, low latency, high connectivity, and high efficiency in terms of energy consumption is increasing [2]. Similar to traditional radio frequency systems, the present communication system also suffers from problems in available spectrum, interference, and security, thus necessitating new communication modes [3]. Visible light communication (VLC) can address these difficulties by optimizing the utilization of light-emitting diodes (LEDs) for lighting and data transmission [4]. VLC has numerous advantages, including immunity to electromagnetic interference and security, because of its limited coverage; it can access unlicensed spectrum and be applied in indoor communication, smart lighting, and IoT networks [5]. However, with the growing influx of connected devices, traditional nonorthogonal multiple access (NOMA)-based techniques may fail to control the necessary resources and spectrum needed to support such intercom interconnected networks [5]. NOMA was introduced to overcome these challenges because it allows many users to access the same frequency and time resources within the same period, and only the power level differs. Thus, NOMA-based techniques increase spectral efficiency, enhance system performance, and ensure that an equal measure is given to users [6]. The integration of VLC with NOMA is referred to as VLC-NOMA, which may be suitable for the needs of 6G. Given that the combination of VLC and NOMA improves the speed of VLC technology and that secure transmission with NOMA helps overcome the problem of multiplexing, the use of this hybrid technology may alter conventional communication systems. However, the realization of VLC-NOMA entails issues, among which the presence of nonlinear distortions, the interference of signals, and the challenges of reconstructing signals on top of each other are the major barriers in attaining VLC-NOMA systems with maximum performance [7]. In recent years,

DOI: https://doi.org/10.54216/FPA.200104

Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

challenges in communication systems have been encountered, particularly with the advent of free access to the Internet; machine learning (ML) algorithms offer potential solutions to these problems [8]. Given that ML involves the learning of complex relations and online tuning of system parameters [9], it can be utilized to enhance the efficacy of VLC-NOMA systems. This work seeks to evaluate existing research on vehicular communication and VLC-NOMA systems, with a specific focus on the application of ML to mitigate technological limitations. It explores the prospects of implementing ML-based VLC-NOMA systems for 6G networks. Despite the advantages of VLC-NOMA systems, the deployment of these systems encounters issues in efficient resource allocation, interference management, and expansion in multiuser systems. Traditional optimization techniques often face challenges because of these systems' nonlinearity and time-varying behavior. ML is perhaps the most helpful among all tools to address such challenges because it provides self-adjustable mechanisms for resource management, signal detection, user selection, and all the processes in associated VLC-NOMA networks [10]. The use of ML techniques is beneficial to several system performance targets; for example, it enhances spectral efficiency and reduces the bit error rate (BER). This systematic review evaluated the status of ML applications, specifically in VLC-NOMA systems, by considering their strengths, limitations, and state of application. This work employed a technique that is based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to complement present studies, classified approaches, and focused on major scale deficiencies, energy saving, and practical use. As a result, insights into the ways through which ML can be employed to successfully accomplish robust, scalable VLC-NOMA systems are provided. The remainder of the paper is structured as follows. Section 2 describes the procedures employed for the PRISMA approach to classify studies relevant to this research. Section 3 discuss the challenges associated with VLC- NOMA based ML System. Section 4 examines the function of ML in tackling difficulties and offers a comparative examination of diverse ML methodologies. Section 5 delineates the study's deficiencies and suggests prospective directions for research on federated learning and hybrid optimization. Section 6 concludes the paper by presenting critical findings and implications for 6G networks.

2. Systematic Literature Review Characterization and Queries

In telecommunication innovation, particularly regarding 6G networks, technologies, such as VLC and NOMA, are important. This systematic review is relevant to the integration of NOMA with VLC. It focuses on performance indicators derived from the application of ML and deep learning models. Specifically, the PRISMA CHECKLIST was used to conduct a systematic assessment of existing systematic reviews and meta-analyses. An electronic search was performed in August 2024 by using different academic databases to retrieve related articles. The academic database search involved four primary databases, namely, IEEE Xplore, MDPI, Science Direct, and Springer, for which another search was conducted on Wiley Online Library, Taylor and Francis Online, Optica, and Tech Science Press, respectively. IEEE Xplore was chosen because it includes a vast collection of more than five million documents in full text covering computer science, electronics, and electrical engineering disciplines. Founded as a chemical research publisher, MDPI has evolved into an open-access publisher of over 390 peer-reviewed journals. The other platforms that were essential to this efficient and extensive search were ScienceDirect, which is known for offering almost unrestricted access to medical and technical journals, and Springer.

Articles on NOMA, including those on performance evaluation using NOMA, VLC networks and ML, 6G and visible light using ML and NOMA, and improvement utilizing VLC or NOMA and artificial intelligence (AI), were searched for. The search process initially yielded 244 articles from 2019 to 2024. The distribution of these articles was as follows: 89 were from IEEE Xplore, 49 were from MDPI, 16 were from ScienceDirect, 8 were from Springer, and 82 were from the other databases. After the articles were filtered for duplicates, their number decreased to 215. The titles and abstracts were reviewed to refine the search, and the articles that were not related to the study were excluded. This procedure left 62 articles for full-text review. The final step involved the assessment of the articles, which led to the identification of 45 articles that met the criteria stipulated for this study

3. Challenges Associated with VLC- NOMA based ML System

The main advantage of NOMA is that it allows several users to simultaneously access the same frequency resource in a nonorthogonal manner, hence improving spectrum efficiency [11]. Similar to code division multiple-access systems, code-domain NOMA (CDNOMA) is based on the principle of numerous users concurrently utilizing identical resources. However, CDNOMA distinguishes itself by employing sparse spreading or nonorthogonal low cross correlation sequences for multiplexing.

CDNOMA) encompasses various strategies, including sparse code multiple access (SCMA), as demonstrated by Zhang et al. [12]. Illustrations of this methodology are available. Power-domain NOMA (PD-NOMA), the second form of NOMA, utilizes power-domain multiplexing to enable several users to use a single resource (such as time, frequency, or code) while allocating different power levels. This approach facilitates nonorthogonal access through superposition coding (SC), allowing for the

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

implementation of sophisticated multiuser detection techniques, such as successive interference cancellation (SIC) or dirty paper coding, which were employed by Hussein and Haburi [13] at the receiver for message decoding

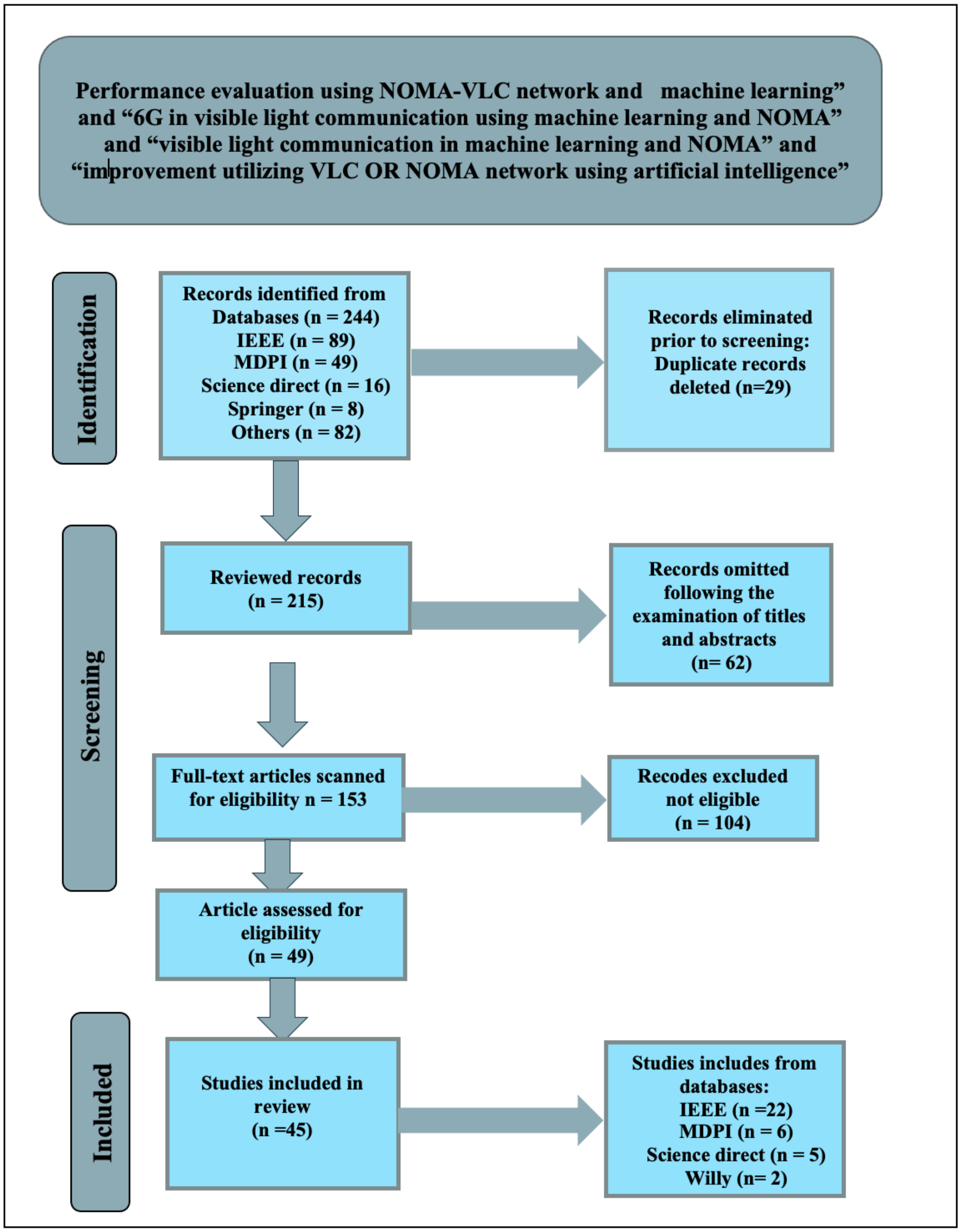

Figure 1. PRISMA flow diagram

A. Power Allocation Challenge

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

The VLC-NOMA power distribution technique differentiates users on the same frequency band. It amplifies power to help customers address channel issues and improve their link. It focuses on optimizing power allocation and beamforming in a multi-LED VLC network to enhance physical-layer security. It also provides bounds for the secrecy capacity region and presents design techniques for to minimize the overall LED transmission power while adhering to quality of service (QoS) and secrecy limitations and to maximize the minimal secrecy rate. In the work of Du et al. [14], optimization problems were addressed efficiently with the help of semidefinite relaxation and successive convex approximation. Simulation analysis revealed that security and system performance are enhanced, a fact that underscores the need to incorporate the best power regulation and beamforming procedures into VLC-NOMA networks. Papannikolaou et al. [15] endeavored to achieve efficient power control to improve network quality. In PD-NOMA, a coalition formation algorithm derived from coalitional game theory is employed to fairly allocate power among users in a manner that is optimally efficient for the individual user and the whole network at large. The researchers employed power control in the proposed utility function, and through computer simulations, they demonstrated that the utility function improves spectral efficiency and achieves user fairness. This result emphasizes the need to manage power in hybrid VLC/radiofrequency (RF) networks for next-generation wireless systems. Shang et al. [16] proposed the multifactor optimal power allocation (MFOPA) strategy to improve power control through VLC systems that use NOMA. Specifically, the MFOPA approach aims to enhance the system's capacity, with consistent emphasis on QoS, user fairness, and eye safety, to address VLC's limited bandwidth. It considers the overlapping disarray in the overlap optimization of the bioconversion of the SIC issue for resolution. The simulation results showed that the developed MFOPA approach maintains a better sum rate and new-user fairness compared with conventional power allocation strategies, such as static power allocation (SPA) and gain ratio power allocation (GRPA). This finding highlights the importance of employing appropriate power management and distribution mechanisms to optimize the performance and resilience of indoor VLC-NOMA systems. In the studies of Zhao et al. [17] and Asagar et al. [11], the authors proposed a power allocation method for optical access correspondence of optical access points (OAPs) and mobile users (MUs) with visible light nonorthogonal frequency division multiplexing based on vehicle-to-vehicle communication (VLC) and disequilibrium multiaccess (NOMA). The networks make up a secrecy optimization NSSC iterative Karush–Kuhn–Tucker (KKT) condition and a security-aware water-filling algorithm. These studies demonstrated that the use of efficient power control techniques suitable for secure VLC systems can improve the signal interference-plus-noise ratio (SINR) and the network security of the system.

Yang et al. [18] addressed the problem of power control for VLC systems that use NOMA to maximize the downlink sum rate subject to imposed QoS, power, and LED constraints. The proposed methodology converts the nonconvex formulation into a convex one by using variable transformation, and Taylor series expansions are solved by iteratively implementing the KKT approach. However, there is no text to work with. Experimental evaluations conducted in an indoor VLC system where users are randomly placed demonstrated that the proposed algorithm performs better than the modified GRPA algorithm. Moreover, it converges to an exhaustive search method in terms of sum rates with low complexity. Yahya et al. [19] proposed to avoid symbol overlap in the overlaid constellation to achieve a near-zero signal-to-error ratio (SER). The optimal power distribution strategy was identified to suppress interference to the first user, and noise was minimized for the second user to optimize SER for this user. The extensive theoretical assessment of the study and the simulation results emphasize the effect of proper power control on reducing SER and enhancing the efficacy of NOMA-based VLC systems.

Rallis et al. [20] examined the optimization of energy efficiency (EE) in hybrid networks that combine VLC and RF technologies. Their protocol seeks to enhance data rates for edge users by employing cooperative relays from central users within the cell. The resource allocation problem is addressed through Dinkelbach's algorithm and sequential convex approximation to maximize EE while ensuring compliance with QoS standards. The simulation results indicated that the protocol effectively leverages the complementary advantages of VLC and RF technologies, resulting in considerable increments in EE compared with benchmark systems. The study stated that future investigations should focus on multicell scenarios, interference management, and user scheduling. Table 1 presents a summary of these challenges.

Table 1: Summary of power challenges in VLC-NOMA systems

Ref.	**Methodology**	**Experiments**	**Results**	**Conclusion**
[16]	Proposes an Optimal Power Allocation (MFOPA) for NOMA-VLC, which optimizes power to maximize capacity while ensuring quality of service, fairness, and eye safety. Uses convex	Simulated in a 7m x 7m x 3m room with varying SINR and interference levels. Compared MFOPA to SPA and GRPA.	MFOPA consistently outperformed SPA and GRPA, maintaining a high sum rate and better fairness, even with increased interference.	MFOPA enhances sum rate and fairness, proving robust for practical NOMA-VLC systems,

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

	optimization, considering interference and residual effects			especially in high-demand scenarios.
[17]	This study presents a hierarchical power allocation algorithm to improve Physical Layer Security (PLS) in NOMA-enabled VLC networks, emphasizing optimizing power for secure communication.	Simulations in a 10m x 10m room with varying user densities, LED angles, and PD FoV test the algorithm's performance.	The algorithm effectively improves Network Sum Secrecy Capacity (NSSC), with better results from more OAPs, narrower LED angles, and smaller FoV. Higher user density reduces NSSC due to interference.	The proposed algorithm successfully boosts PLS in dynamic NOMA-VLC networks, optimizing power to improve NSSC across different conditions
[15]	Proposes a coalitional game theory approach for user grouping in hybrid VLC/RF NOMA networks, focusing on optimizing power allocation.	Simulations in a 10x10x4m room with multiple access points test the algorithm.	The method improves spectral efficiency and fairness, outperforming traditional approaches.	The algorithm enhances performance and robustness in hybrid VLC/RF NOMA networks.
[14]	Proposes secure beamforming for NOMA VLC to minimize power and maximize secrecy rates under constraints.	Simulations test the method in multi-user VLC networks with varying QoS and LED setups	Effective in reducing power and enhancing secrecy rates, especially with higher dimming levels.	Improves security and efficiency in NOMA VLC networks under different conditions.
[20]	Proposes a cooperative NOMA protocol for VLC/RF networks to optimize energy efficiency using advanced algorithms	Simulations assess EE under different QoS and network conditions	Significantly improves EE, especially in low QoS scenarios and with strong RF channels.	Enhances EE in hybrid VLC/RF networks, showing robust performance.
[18]	Propose a power allocation strategy for NOMA-VLC to maximize the sum rate while adhering to QoS and power constraints by applying convex optimization.	Simulations compare the proposed algorithm with GRPA under different SNR and user scenarios.	The algorithm outperforms GRPA in sum-rate efficiency across various conditions.	The strategy improves sum-rate in NOMA-VLC systems, surpassing GRPA.
[19]	A survey on NOMA error rate analysis (BER, SER, PEP) for both downlink and uplink, focusing on modulation schemes and power allocation strategies.	Simulations and theoretical analysis of various NOMA configurations, including different fading channels and modulation schemes.	Improved spectral efficiency and error performance through optimized power assignments, with key sensitivity to modulation and channel conditions.	Summarizes findings, identifies research gaps, and suggests future work on optimizing SIC and exploring new modulation and coding schemes.

The studies above revealed that power control in VLC-NOMA systems is vital in improving system performance, security, and user equitableness. Methods, such as dynamic power control, coalition formation, and Multi objective optimization, can enhance the system's SE and SC. Furthermore, adding ML to real-time optimization and creating superior interference

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Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

management techniques can increase system reliability, especially in high-density networks. Further consideration of energy saving, particularly in hybrid VLC/RF networks, and analysis of multicell scenarios are important for the future development of scalable and sustainable VLC-NOMA systems. These enhancements can incorporate the attributes necessary to address next-generation wireless communication networks.

B. Multiple-input Multiple-output Challenge

Multiple-input, multiple-output (MIMO) channels have substantial advantages in capacity and demonstrate considerable improvements compared with single-input, single-output channels, as established by Liu et al. [21]. MIMO VLC-NOMA, a VLC system that integrates MIMO and NOMA algorithms, exhibits considerable potential for enhancing spectral efficiency and system capacity. Power allocation is tailored to the specific conditions of each channel to maximize capacity and efficiency. Multiple antennas are utilized at both ends, with each user being assigned to a separate beam.

Precoding techniques and SIC are used in multiuser MIMO-VLC systems to segregate signals and reduce interference. Naser et al. [22] studied the performance of rate splitting multiple access (RSMA) in terms of spectral efficiency and reliability in multi-input, single-output (MISO)-VLC systems. Their proposed method is based on modeling a MISO VLC system with N LEDs and two users with single-photon detectors. For real-time weighted sum rate (WSR) optimization, user messages are partitioned as common and private parts to maximize WSR under the constraints of LED power and channel characteristics. Experiments showed that in a 5 × 5 × 4 m^3 room with different user positions and LED configurations, RSMA outperforms NOMA and SDMA in terms of WSR under conditions with high signal-to-noise ratios (SNRs) because of effective interference and channel correlation management. RSMA that combines NOMA and MIMO techniques results in a unified design that effectively improves VLC system performance. Wang et al. [23] introduced the normalized logarithmic GRPA (NLGRPA) method to enhance the performance of NOMA-based MIMO-VLC systems. The NLGRPA scheme considerably increases the total rate that can be obtained in MIMO-VLC networks by using optical channel gains obtained from different LEDs, and optimal power distribution among users is realized. The power allocation schemes, such as GRPA and normalized gain difference power allocation (NGDPA), are conventional approaches, but they are not better than the proposed NLGRPA scheme. The research provided proof by performing simulations, which showed that NLGRPA is ideal for situations with many users and where the channel conditions change over time; its sum rate reaches 55%. The algorithm is extremely good at putting energy in the correct place for Mooberra such that no other strategy can be better than it.

Jha et al. [24] studied the NOMA-MIMO system in VLC by using zero forcing (ZF)-SIC and minimum mean square error (MMSE)-SIC equalizers. Their setup simulated a VLC system with two LEDs and two photodiodes, where the power is assigned based on the closeness of the users. The work investigated the BER performance of using orthogonal frequency-division multiplexing (OFDM) and quadrature amplitude modulation at different SNRs. The experiments were conducted in a 5 m × 5 m × 3 m room and showed that the BER of MMSE-SIC is 3 dB better than that of ZF-SIC at the same SNR. That is, the effect of MMSE-SIC on interference and noise suppression is excellent, so it is a candidate for future VLC systems.

Zakavi et al. [25] described a multiple-user massive MIMO-OFDM VLC system that, along with capacity enhancement, eliminates private inter-user interference (IUI) in indoor scenarios. Through the utilization of an array of LEDs responsible for downlink transmission, which resulted in different time delay issues, disparate user experience, and a time shift, the authors dealt with the problem of introducing different channel gain and phase differences into the frequency domain that makes the process increasingly complicated. They analyzed the performance of three linear precoding schemes, namely, maximum ratio transmission (MRT), MMSE, and ZF, in IUI mitigation. The experiment simulations confirmed that the developed scheme has the highest improvement among the compared methods, and MMSE and ZF are effective only in situations where the number of LEDs is much larger than that of the users. MRT is good under conditions where the ratio is small. The results revealed that the proposed scheme improves the spectral efficiency of the system and reduces downlink optical power. Accordingly, the proposed scheme for VLC works in multiuser cases.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

Table 2: The challenges concerning MIMO in the VLC-NOMA system.

Ref.	Methodology	Experiments	Results	Conclusion
[21]	This study examines a power allocation algorithm for MIMO-NOMA within visible light communication (VLC) systems. The study introduces a low-complexity approach termed Normalized Gain Difference Power Allocation (NGDPA) to enhance sum-rate performance by utilizing users' channel conditions.	The performance of a 2×2 MIMO-NOMA VLC system utilizing various power allocation methods (NGDPA versus GRPA) was assessed through simulations. The system configuration involves multiple users, and the outcomes are evaluated against conventional OFDMA systems.	The NGDPA method demonstrated notable enhancements in achievable sum rates, especially in scenarios involving a greater number of users and larger user offsets from the LED. An improvement of up to 29.1% in the sum rate was observed when compared to the GRPA method.	The NGDPA method effectively improves the sum rate in MIMO-NOMA VLC systems while maintaining low computational complexity. The method shows potential for future high-speed multi-user VLC systems, particularly with an increasing number of users.
[22]	Introduces RSMA in MISO VLC, combining NOMA and SDMA. Uses message splitting, linear precoding, and SIC for decoding.	Simulates RSMA in a two-user MISO VLC system with configurations of 2 and 4 LEDs, analyzing performance under different SNRs and user separations.	RSMA demonstrates superior performance compared to NOMA and SDMA in terms of WSR, particularly under high SNRs, due to its flexibility and ability to manage channel correlations.	RSMA is superior to NOMA and SDMA in MISO VLC , offering better spectral efficiency and data rates. Future work should focus on optimizing precoding and addressing practical challenges
[23]	Proposes NLGRPA to optimize power allocation in NOMA-assisted MIMO-VLC networks through the ordering of LED channel gains.	Simulated in a 5x5x3 m³ indoor MIMO-VLC network, comparing NLGRPA with GRPA and NGDPA across different user setups.	NLGRPA outperformed GRPA and NGDPA, with sum rates up to 55.7% higher, especially when the number of users was large.	NLGRPA enhances the sum rate in NOMAMIMO-VLC networks, demonstrating superiority over current methods.
[24]	Analyzed NOMA MIMO-VLC using ZF-SIC and MMSE-SIC techniques to enhance BER performance.	Simulated a 2x2 MIMO-VLC system with two users to compare BER between ZF-SIC and MMSE-SIC.	MMSE-SIC improved BER by 3 dB over ZF-SIC at the same SNR, showing superior error reduction.	MMSE-SIC is more effective than ZF-SIC for improving BER in NOMA MIMO-VLC systems.
[25]	Proposed MU-mMIMOOFDM VLC system employs ZF, MMSE, and MRT precoding to mitigate inter-user interference in complex channels.	Simulated in a 5x5x3 m³ room, this study compares ZF, MMSE, and MRT precoding techniques in terms of spectral efficiency.	MRT excels with fewer LEDs, while ZF and MMSE are better with more LEDs. Achieved up to 44 dBW improvement in power efficiency.	The proposed system improves spectral and power efficiency, especially with large LED arrays, ideal for VLC applications.

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Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

Altogether, the abovementioned studies support the practical role of MIMO-NOMA in doubling the spectral efficiency of VLC systems, tripling the system capacity, and mitigating system interference. For instance, RSMA, NLGRPA, and new distinct precoding methods react much better than DOA in several multipath circumstances and under multiuser and high-SNR conditions. These approaches provide an efficient means of avoiding interference and controlling the power distribution in a way that provides high sum rates on the overall system reliability. Such enhancements are possible with fine-tuning power distribution policies, complex precoding, and application of MIMO-NOMA in conjunction with other top-tier techniques, such as OFDM and adaptive modulation. Such enhancements may further enhance the spectral efficiency and system performance of indoor VLC networks. Therefore, MIMO-NOMA could be a key enabling technology for next-generation VLC programs.

C. ML in the VLC–NOMA System

ML is a powerful technique to effectively improve the implementation of VLC in various contexts, including vehicular and indoor environments. The combination of ML techniques with VLC and NOMA achieves noise reduction, channel modeling, and resource allocation. Contemporary research has proven that ML integration can enhance signal quality by enhancing SNR and decreasing BER. The improvement in the general performance of systems is a major factor in the advancement of fifth generation and beyond wireless networks.

Khadr et al. [26] explained the possibilities of using massive MIMO technology for VLC in the context of IoT. Their work was dedicated to augmented spatial modulation (ASM), which the authors proposed to resolve the problems of conventional SM in highly correlated VLC channels that are typical in indoor scenarios. ASM is a reliable solution to enhance data throughput in VLC because CSI and channel uniqueness that affect conventional spatial modulation systems are avoided. The authors further improved the ASM framework by incorporating ML algorithms, such as support vector machine (SVM), linear regression, and neural network (NN), with receiver performance optimization in massive MIMO systems to reduce complexity. The findings indicated that the proposed ML-based ASM system can maintain a transmitter identification rate of more than 99% even when up to 1,000 transmitters are present. Furthermore, the application of the NN-based approach demonstrates high efficacy; it provides stable performance irrespective of the number of transmitters and can be used to address massive IoT implementations. The study highlighted the trade-off between computational complexity and system performance and demonstrated how ASM can provide high throughput with low complexity communication in large MIMO IoT VLC systems.

Turan and Coleri [27] proposed an ML approach for channel modeling in vehicular VLC (VVLC) systems. Deterministic and stochastic models usually exhibit poor performance in the modeling of VVLC channels and their performance under different environmental conditions. To address these issues, the authors employed ML algorithms, including multilayer perceptron (MLP), radial basis function–neural network (RBF-NN), and random forest (RF), for high CFR and channel loss prediction. They observed that these models provide a better solution to channel impairments compared with conventional curve-fitting methods and have the least RMSE in predicting losses. The analysis also examined how aspects, such as ambient light and inter-vehicular distance, influence VVLC channel characteristics. As expected, the devised models provide good adjustments under various physical conditions, indicating the applicability of the approaches in practical vehicular communication systems.

He and Ali [28] highlighted the transformative function of ML and deep learning in advancing VLC systems. Their review focused on how these technologies address critical challenges in VLC, such as signal modulation, photon counting detection, and visible light positioning (VLP). They emphasized that deep learning models, such as DeepGOMIMO, substantially enhance MIMO systems by enabling CSI-free detection through the innovative mapping of transmitted information onto active LEDs. Additionally, ML techniques, including gated recurrent units (GRUs) and convolutional neural networks (CNNs), markedly improve the accuracy of 3D VLP systems by effectively managing line-of-sight (LOS) and non-line-of-sight (NLOS) links.

These advancements highlight the potential of using ML and deep learning to enhance data rates and reliability and effectively connect theoretical insights with practical applications in VLC technology. Affan et al. [29] built a P-NOMA VLC system that employs ML for indoor localization and resource allocation. The authors compared random forest regression (RFR) and SVM methods and reported that the accuracy of RFR (0.19 m error) is higher than that of SVM (0.3 m error). The system, by using simplified GRPA (S-GRPA) and a Euclidean distance matrix (EDM) to predict the lost signals' locations, can pinpoint the predicted locations of signal loss. Simulations showed that RFR, in tandem with S-GRPA, efficiently assigns power and reduces BER at various SNRs, which is the reason for the system's efficiency increase. Smirani et al. [30] presented a novel way of attaining channel estimation improvement in NOMA-based 5G systems via ensemble learning model-based stacked generalization for channel estimation (SGCE). Multiple ML techniques, including random forest, gradient boosting, light gradient boosting machine, support vector regression, extremely randomized trees, and extreme gradient boosting, served as the meta-learner and made up the SGCE model. By leveraging the unique strengths of such models, the SGCE scheme substantially enhances the quality and efficiency of channel estimation, with an average accuracy of 98.4% and an F1-score of 98.5%. The results revealed that SGCE considerably outperforms conventional approaches and NN models, thereby offering a firm and viable solution to accurate NOMA scenarios that are highly complex to enhance channel estimates, thus determining next-generation wireless networks' performance. The ML challenge faced by the VLC-NOMA system is presented in Table 3.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

Extant studies have demonstrated how ML, with its versatility, is the best solution for the VLC-NOMA system in terms of performance and stability. Overall, applying learning algorithms, such as k-nearest neighbor (KNN), SVM, and deep learning, can resolve issues, including noise suppression in VVLCs and channel modeling optimization and high data transmission in MIMO systems. All these methods improve SNR, BER, channel estimation accuracy, and system efficiency. However, many areas can still be improved. An example is the use of ensemble learning and NNs that are complex and difficult to scale. Moreover, next-generation wireless communication systems that use VLC-NOMA can be greatly improved by the proper utilization of ML algorithms in real-time adaptive systems and their development in multiuser and Multi environment scenarios.

Table 3: Summary of machine learning in VLC- NOMA system

Ref.	Methodology	Experiments	Results	Conclusion
[26]	Proposed an Augmented Spatial Modulation (ASM) system for Visible Light Communication (VLC) utilizing Massive MIMO integrated with machine learning methods such as Support Vector Machines (SVM), Logistic Regression (LR), and Neural Networks (NN) to improve receiver performance.	Simulated an ASM system with up to 1000 transmitters for the purpose of judging the performance of the transmitter identification rate and the system in highly correlated indoor VLC channels	In the ML-based ASM scheme, the transmitter identification accuracy was above 99% with high stability, where the offered communication was of low-complexity and at a large throughput	Further, the proposing of ASM incorporated with ML algorithms makes a great solution in the large MIMO IoT VLC systems with good stability of complexity and performance.
[27]	Used MLP, RBF-NN, and Random Forest in channel modeling in VVLC systems for the enhancement of CFR and channel loss.	An effort was made to simulate the ML-based model's performance in various situations and compare it to the conventional curvefitting methods for channel loss and performance. The simulations were successful.	ML based models yielded better channel loss prediction with lower RMSE than conventional methods and they are also capable of adapting with the changes in environmental factors	MVLA augment the nominal channel modeling for VVLC systems and making them more suitable in real-world environments.
[28]	The document highlights the application of machine learning (ML) in Visible Light Communication (VLC) systems to optimize signal processing, augment data rates, and enhance system reliability.	ML-based experiments include using neural networks for signal detection, 3D positioning, and handling line-of-sight (LOS) and non-line-of-sight (NLOS) signals in VLC systems.	ML-based experiments include using neural networks for signal detection, 3D positioning, and handling line-of-sight (LOS) and non-line-of-sight (NLOS) signals in VLC systems.	ML is key to advancing VLC systems, with future work focusing on integrating ML for better signal processing and real-time application performance.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

[29]	Utilized Random Forest Regression (RFR) and SVM for indoor localization in VLC systems under shadowing.	Compared RFR and SVM for positioning accuracy using RSS and AoA; used EDM for position recovery when signals were lost.	RFR achieved better accuracy (0.19 m) and enabled effective power allocation in a multi-agent VLC system.	RFR improves VLC localization and power management, with future tests planned for real-world application.
[30]	Proposed SGCE model using ensemble learning with six ML models to enhance channel estimation in NOMA systems.	SGCE outperformed traditional methods like MMSE and neural networks in simulations, showing better accuracy and throughput	Achieved 98.4% accuracy, 98.1% precision, and 98.5% F1-score, surpassing other models in SNR and throughput gains.	SGCE offers a significant improvement in channel estimation, with potential for further optimization and real-world validation.

D. Deep Learning in the VLC–NOMA System

Jha et al. [31] implemented the deep learning approach in the VLC–NOMA system to enhance the usefulness of NOMA in VLC. This method addresses the problems linked to imperfect SIC. The study used CNN, long short-term memory, and deep neural network (DNN) processes to eliminate the disruptions caused by insufficient SIC that diminish system performance. MATLAB simulations proved to be a substantial boost for the NN-based detection algorithms. In contrast to previously known methods, these new algorithms excel even in removing interference from the signals in the system. The most notable of these methods is CNN. CNN can perform cancellation in a manner that is exceptionally effective, allowing the communication of the signal to the intended receiver despite the severe interference at a low SINR of −1 dB. These new models of deep learning can be regarded as reliable tools for increasing the efficiency of NOMA-VLC systems, making them effective for the examination of the efficacy of SIC methodologies.

Shrivastava et al. [32] proposed a Deep Q-Network (DQN) learning-based method that is responsible for downlink resource allocation optimization in hybrid RF/VLC systems. This methodology adopts a DQN learning model to enhance bandwidth allocation, power distribution, and user association in a downlink hybrid RF/VLC environment. The experimental results suggested that the DQN algorithm outperforms conventional forms of optimization, such as exhaustive search and Q-learning, in improving the achievable sum rates and minimizing the number of iterations required for convergence. The results clearly indicated that DQN-based optimization achieves improvements in the parameters of the problem; for example, it attains an increase of around 10% in the sum rate and minimizes the convergence iterations by 54%. This finding indicates that the approach is highly effective, and it can be applied in real time in hybrid RF/VLC networks.

Furthermore, Wang et al. [33] developed energy-efficient unmanned aerial vehicle (UAV) networks by utilizing deep learning technologies. The methodology they introduced integrates CNN and GRU as an illumination distribution predictor, thereby optimizing the location of UAVs and energy efficiency. According to experiments using real data, this technology has the potential to reduce transmitted power by up to 68.9%, which is a crucial advantage over traditional methods. Deep learning's effectiveness in enhancing the deployment of UAVs is successfully employed. DNN-GenSM is a deep learning-based detection strategy introduced by Wang et al. [34]. It is intended to improve the efficiency of VLC systems through generalized spatial modulation (GenSM). This neural network integrates all the fundamental signal-processing modules into a singular platform and consists of algorithms, such as equalization, decoding, and bit combining. The BER performance of DNN-GenSM approaches that of the maximum likelihood method by perfectly realizing the simulation of ZF and MMSE. Thus, DNN-GenSM is an immense improvement of common two-step detectors. DNN-GenSM achieves its objective with reduced computational complexity, especially in cases with high PAM levels. Thus, it is a feasible, accurate remedy for the issues in multi-LED VLC systems. This study reviewed how AI could automate the learning process in VLC systems. Such methods can produce excellent detection outcomes and reduce the expenses of computation via data mining.

Al Hammadi et al. [35] developed an innovative discrete optimization programming (DQL) method to improve the management of indoor NOMA-VLC networks by utilizing available resources efficiently. In their study, a discrete decision-making framework was combined with DQL to determine the most effective power allocation strategy and LED angle of irradiation.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

The experiment results demonstrated that DQL is superior to conventional algorithms, such as the genetic algorithm (GA) and differential evolution, in terms of stability, results, and accuracy. The DQL technique has a high average sum rate and energy efficiency even in high-density user circumstances. These findings indicate that DQL may be utilized advantageously to address the challenges and security issues of VLC systems, and it can serve as an operative aspect for the future of communication networks.

Meanwhile, Asif et al. [36] employed deep learning to improve NOMA in multiuser VLC systems. Their work included comparisons of OAM modulation with OFDM/IM. The main and most important finding of their work is that OAM-IM outperforms OFDM-IM in BER, particularly under low-SNR conditions. Recent progress shows that compared with related ML techniques, CNN-based detectors yield a larger reduction in detection errors despite being traditional. The usefulness of deep learning technology for future communication systems has been revealed by the integration of such technology into the SIC task; the integration improves system robustness and spectral efficiency.

Salama et al. [37] proposed a way to increase the BER performance of NOMA-based VLC systems via MIMO with the use of deep learning methods. They gathered data on deep learning models, such as ResNet50V2 and InceptionResNetV2, and examined the problem of how to deal with complexity and how to improve the learning rate to reduce overfitting. They aimed to enhance performance via the improvement of spectral efficiency using diverse modulation schemes, such as on–off keying (OOK) and L-pulse position modulation (L-PPM). Simulations showed that ResNet50V2 had a more substantial outcome than InceptionResNetV2; it realized a maximum of a 31% increase in BER, especially under less-than-ideal SIC conditions where ResNet50V2 was outstanding. This research proved that deep learning could be employed to improve NOMA-MIMO-VLC systems, particularly in difficult multiuser environments, by striking a balance between BER and spectral efficiency. This challenge is presented in detail in Table 4.

The reviewed studies revealed how deep learning enhances the performance of VLC-NOMA systems in the presence of issues, such as imperfect SIC, resource allocation, and signal detection. The analyzed approaches based on CNN, DQN, and DRL outperform the benchmarks in terms of SNR, BER, spectral efficiency, and system resilience. Deep learning models are superior to conventional approaches, especially in high-degree high-traffic networks, so they are suitable for next-generation communication platforms. The following are areas for further improvement: fine-tuning of deep learning models to reduce the computational demand, real-time learning capability, and expanding the applicability of networks, including combined VLC–RF and multiuser systems. Through the integration of these advanced deep learning techniques, VLC-NOMA systems can achieve improved reliability, efficiency, and scalability, thus paving the way for future improved reliable wireless communication networks.

Table 4: Summary of deep learning in VLC- NOMA system

References	Methodology	Experiments	Results	Conclusion
[31]	Integration of machine learning (ML) in VLC for signal processing, modulation, and positioning.	ML applied in MIMO/OFDM systems, SiPM sensor evaluation, and CNN/GRU-based 3D positioning.	ML improved positioning accuracy to centimeter-level and enhanced sensor performance in low-light.	ML significantly boosts VLC performance, especially in positioning, but real-world application challenges persist.
[32]	This research optimizes user association, power consumption, and downlink resource allocation in hybrid RF/VLC systems using Deep Q-Network (DQN) learning.	Simulations were conducted to evaluate DQN's performance in maximizing the data rate compared to conventional optimization methods in a hybrid RF/VLC setup.	DQN showed a 10% improvement in achievable sum-rate and a 54% reduction in convergence iterations compared to traditional methods, highlighting its effectiveness.	DQN-based learning significantly improves resource allocation in hybrid RF/VLC systems, offering a robust solution with better performance than existing algorithms.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

[33]	The research optimizes the deployment of UAVs using Visible Light Communication (VLC) by forecasting illumination distribution using a mix of Convolutional Neural Networks (CNNs) and Gated Recurrent Units (GRUs).	Simulations were conducted using real illumination data to evaluate the impact of the CNN-GRU model on UAV deployment and power efficiency.	The CNN-GRU model achieved a 68.9% decrease in transmission power in comparison to traditional methods by accurately predicting illumination and optimizing UAV positioning.	Deep learning, particularly CNNs and GRUs, effectively enhances UAV deployment strategies in VLC networks, significantly improving energy efficiency.
[34]	Proposed a DNN-GenSM detection scheme for VLC systems, integrating signal processing into one neural network.	Simulations compared BER performance across different SNR levels with conventional detectors	DNN-GenSM achieved near-optimal BER with lower complexity than traditional methods, especially at higher PAM levels	DNN-GenSM offers an efficient, accurate solution for VLC signal detection with reduced computational complexity.
[35]	Using Deep Q-Learning (DQL), NOMA VLC systems can improve power allocation and LED orientations.	A comparison of DQL with Genetic Algorithm (GA) and Differential Evolution (DE) was drawn from simulations.	DQL showed faster convergence and higher sum rates than GA and DE	DQL enhances resource allocation in NOMA VLC, with superior performance and efficiency.
[36]	The paper explores OAM and OFDM with Index Modulation (IM) in a multiuser VLC system, using a CNN-based deep learning receiver.	The simulations examined the performance of BER in 2-user and 3-user NOMA-VLC systems with perfect and imperfect SIC, as well as OOK and L-PPM modulation.	In particular at higher SNRs, OAM-IM achieved better performance than OFDM-IM. When compared to the ML approach, the CNN-based receiver offered superior BER.	OAM-IM and deep learning-based detection show promise for enhancing VLC system performance.
[37]	The paper proposes improving BER in NOMA-VLC systems using deep learning models, specifically ResNet50V2 and InceptionResNetV2, applied to MIMO setups.	Simulations compared BER performance using OOK and L-PPM modulation with perfect and imperfect SIC for 2-user and 3-user NOMA-VLC systems.	ResNet50V2 outperformed InceptionResNetV2, showing better BER performance, especially in higher complexity MIMO scenarios. Improvements of up to 31% were observed with ResNet50V2.	As a potential strategy for future communication systems, deep learning and ResNet50V2 in particular greatly improves BER performance in NOMA-VLC systems.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

F. Metaheuristic algorithms in the VLC-NOMA system

Metaheuristic algorithms are versatile optimization techniques for solving difficulties in NOMA systems, especially in terms of VLC. These algorithms include particle swarm optimization (PSO) and Harris–Hawks optimization (HHO), which are being increasingly adopted to improve system capability, power sharing, user pairing, and UAV deployment. These techniques, which can solve nonconvex, NP-hard optimization problems, yield substantial gains in energy efficiency, spectral efficiency, and system reliability; they are indispensable for the creation of emerging wireless communication networks. To optimize user pairing in NOMA systems, Masaracchia et al. [38] proposed a PSO-based methodology that aims to reduce transmission power while maintaining QoS. The authors used PSO to efficiently solve the problem after formulating it as a mixed-integer linear program. By applying PSO in distributed local area networks, the authors showed through experiments that a power saving goal of a 60%–100% load reduction can be achieved in a data-free subchannel without a substantial drop in QoS while on a nonglossy link. Moreover, the generation of cryptographic keys by using quantum key distribution (QKD) technology based on the availability of photon polarizations and phase details through crypto functions was highlighted in the study. The main contribution of this work is that it provided a mechanism that can be incorporated into existing key distributed systems for the quick generation and security of keys over shared channels. Security issues related to key management can be resolved by the proposed approach, which minimizes delay in the key establishment process and is thus suitable for applications where such a process is often a bottleneck. Successful trials demonstrated the commercial viability of the proposed technique in a real-world cryptographic environment. The latest innovation in this field is the possibility of improving multiuser efficiency through the introduction of relay nodes in parallel digital information broadcasting. In this hybrid system, the total available time for data transmission is divided among simultaneous users, which can lead to efficient multiuser throughput because of diversity gain. The basic principle of the system is that a certain part of the source data is delivered to the relay nodes via broadcast technology; then, through point-to-point transmission, the nodes deliver the information to the intended users. The way γ is adjusted in the relay node can result in the wastage of a small amount of energy, but this will not decrease the overall throughput because users are logged on simultaneously. Instead of having the end user [39] use the complete transmission power of the base station (BS) to achieve good channel conditions, the relay nodes are adjusted in such a way that they can overcome the poor channel conditions of users who are located far from BS. The results of the study demonstrated that even when the local operation affects channel quality, LDPT could maintain maximum FDP across all users regardless of the number of simultaneous users. Given this flexibility, the system's throughput increases.

In [40], a multifaceted analysis was conducted to evaluate the performance of a 2.4 GHz wireless local area network (WLAN) through computer simulations. This research investigated the probability of channel overloading in WLAN as a preliminary step in a thorough network performance study. The corresponding evaluations were conducted on four different categories with different workloads. The resource allocation ability of wireless connections under different load conditions, the number of users versus the channel, and the capabilities and features provided by different network configurations were the major points of observation. Only a certain load was used in the other setups. One of the users was the focus, and the other ones were normal users. The modes of the wireless connections consumed a normal share of the link's capacity, whereas users with a high-capacity demand appeared in the burst mode of the link. WLAN traffic was then recreated through the models developed at the previous stages. After the peak-hour data were simulated in all the setups for several weeks to generate the preliminary results, the statistics were further investigated. The results were enhanced by integrating theoretical knowledge into the findings of the trial. The results of this research can be used in real-world applications of the proposed algorithm for load balancing and resource allocation.

In [41], the PSO technique, which imitates the social behavior of living organisms, was used to search for the optimal values of multiple objectives of an organization. The findings revealed that PSO is ideal for finding a satisfactory solution for a planting layout planning scheme to minimize the maximum distance from the source to the consumer and the overall process time and cost of material transport. The study highlighted how metaheuristic algorithms can improve positioning accuracy in VLP systems for practical applications. Table 5 provides a summary of this challenge in the VLC-NOMA system.

Table 5: Summary of metaheuristic challenges in the VLC- NOMA system

References	Methodology	Experiments	Results	Conclusion
[38]	In order to reduce transmission power consumption without sacrificing quality of service, this work introduces a Particle Swarm	Simulations evaluate the PSO-based user-pairing scheme against random user-pairing across	PSO significantly reduces power requirements compared to random pairing, with efficiency	Optimizing user pairing in NOMA systems using a PSO-based technique reduces power utilization

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

	Optimization (PSO) method for user-pairing in NOMA systems.	various QoS thresholds and sub-channel numbers.	gains ranging from 45% to 80%.	and satisfies QoS restrictions.
[39]	Reviews power allocation, user grouping, and resource management in uplink NOMA using game theory and optimization algorithms.	Compares various algorithms and models for managing power and user grouping in uplink NOMA.	Highlights the effectiveness of game theory and optimization in improving efficiency and performance.	Identifies remaining challenges in interference management and computational efficiency in uplink NOMA.
[40]	The paper uses **Particle Swarm Optimization (PSO)** to dynamically adjust receiver FOVs in VLC networks, reducing interference by minimizing channel correlation. The fitness function evaluates sum rate, channel condition, and LOS blockage.	Simulations tested various particle and iteration combinations. A **memory-assisted PSO** was used for faster optimization in scenarios with user mobility.	PSO-based FOV tuning improved **network sum rate** and reduced **LOS blockage**. Memory-assisted PSO accelerated convergence with minimal performance loss.	PSO effectively optimizes FOVs, enhancing network performance by balancing interference reduction and throughput, especially in dynamic environments.
[41]	The paper uses **evolutionary algorithms** (PSO, GWO, JAYA, SSA, CSO) to optimize LED placement in VLP systems, minimizing positioning error in a 5m x 5m room. The positioning accuracy is evaluated using the **p10–90 positioning error metric**.	Simulations tested the algorithms in a room with 4 LEDs, comparing optimized placements to traditional geometric layouts. Real-world experiments validated the results.	**GWO** achieved the lowest positioning error, outperforming traditional square and triangle configurations. **PSO** also showed potential for further improvement.	Metaheuristic algorithms like **GWO and PSO** significantly improve LED placement, reducing positioning error and enhancing VLP performance in real-world applications

According to the studies examined above, metaheuristic algorithms, such as PSO and HHO, are used to control power, pair users, and deploy UAVs in a NOMA-based VLC system. These approaches have been shown to provide enhanced energy efficiency improvements in sum-rate performance, in addition to demonstrating much more equitable system performance compared with conventional approaches, such GA random deployment methods. By combining metaheuristic algorithms with ML, the former is endowed with additional capabilities for real-time, nonconvex optimization problems. Such improvements may include the integration of different metaheuristic algorithms and the application of such approaches in dynamic multiuser environments to enhance the robustness, scalability, and performance of next-generation wireless networks.

4. Strength and limitation of ML technique

ML approaches implemented within VLC-NOMA systems provide novel solutions to deal with various intricate issues regarding power optimization and interference management as well as resource allocation. Supervised learning performs power allocation and channel estimation with high accuracy in static settings that have labeled data sets, yet this method requires substantial training time and needs labeled data to function correctly. RL demonstrates excellent capability in dynamic circumstances because it finds optimal resource allocation strategies by learning from system communication in real-time vehicular modes yet requires high computational power. The efficient adjustment of Deep Neural Networks (DNNs) reduces both interference and predicts complex channel behaviors, but they require substantial hardware support because of their high computational needs and extended training times. The combination of Metaheuristic hybridization with Machine Learning

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

approaches makes use of Genetic Algorithm (GA) together with Particle Swarm Optimization (PSO) and ML models to achieve multi-objective optimization results but developers face complexities when creating them and there is low generalization ability for different applications. Table 6 represents these techniques with their accuracy levels along with scalability and computational efficiency and it defines the strength and restriction points of VLC-NOMA systems.

Table 6: Summary of ML techniques and their limitations

ML Technique	Key Use Case in VLC-NOMA	Accuracy	Scalability	Computational Efficiency	Strengths	Limitations	References
Supervised Learning	Channel estimation, power allocation	High	Moderate	Moderate	Easy to implement, interpretable	Requires labeled data	[27], [29]
Reinforcement Learning	Resource allocation, dynamic environments	High	High	Low	Learns from interaction, adaptive	Computationally intensive	[32], [34]
Deep Neural Networks (DNNs)	Complex channel prediction, interference mitigation	Very High	High	Low	Handles non-linear problems effectively	High training time	[35], [37]
Federated Learning	Decentralized model training	Moderate	Very High	High	Privacy-preserving, scalable	Communication overhead, complex setup	[35], [38]
Hybrid Metaheuristic + ML	Multi-objective optimization	High	High	Moderate	Combines strengths of ML and optimization	Complex design, hard to generalize	[38], [39]

This comparative analysis elucidates the advantages and disadvantages of ML techniques in VLC-NOMA systems. Although approaches, such as RFR and DNN, show high accuracy and performance, they encounter scalability and computational difficulties. Federated learning and metaheuristic methodologies are viable alternatives for privacy preservation and adaptive optimization; however, the intricacy of their implementation requires attention. Subsequent research should concentrate on hybrid methodologies that integrate these strategies to balance accuracy, scalability, and efficiency.

5. Gaps and underrepresented areas

The systematic review demonstrates important developments regarding the integration of VLC with NOMA together with ML tools, but researchers need to address persistent research gaps before practical implementation becomes feasible. Few researchers implement experimental testing of theories since their studies rely primarily on theoretical models and testing only through simulations resulting in confined application scope. Future research must direct its focus to conducting field tests using hardware systems to validate both practical design and operational integrity of ML-based VLC-NOMA network systems. Future research needs to tackle the scalability challenges of multi-user networks because existing research mostly studies networks with a single user or small user groups despite the known complexities of extensive and flexible 6G networks which confront severe intercell interference and mobility problems. The implementation of edge AI with distributed resource allocation and scalable ML methods should be developed to address this issue. Research has not sufficiently investigated operational energy efficiency as well as computational trade-offs while still utilizing the benefits from ML for spectrum efficiency and bit error rate (BER) improvements. Energy efficiency stands as a vital requirement for sustainable 6G networks

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

where IoT and edge computing operate thus a lightweight ML system needs development to use pruning and quantization with hardware-accelerated inference. Current research has barely begun to explore the possibilities of hybrid and multi-disciplinary approaches since only few studies exist which combine metaheuristic algorithms (such as PSO and GA) with ML to optimize resource allocation in interference management. Additional research studies must investigate how these merged strategies can boost system operation. Research related to VLC-NOMA has minimal exploration of emerging ML paradigms that include federated learning together with edge AI and transfer learning because these paradigms provide real-time adaptability through decentralized processing. The investigation should proceed to evaluate deployment possibilities in privacy-protecting distributed model training architectures and decision-making systems, which work with limited resources.

The immediate need exists to focus on security and privacy matters affecting ML-based VLC-NOMA systems, which includes adversarial attacks and data protection challenges. Secure development of ML frameworks, which integrate differential privacy together with adversarial training and secure model training protocols, will improve system resistance. These network gaps involving experimental evaluation with scalability improvements and energy optimization while adopting hybrid procedures along with emerging machine learning approaches and security enhancements form essential requirements for VLC-NOMA system implementation in 6G networks toward building adaptable and secure wireless connection methods.

6. Discussion

The review of multiple factors affecting the improvement of NOMA in VLC systems brings real improvements in the dimensions of analytic facility and power allocation, MIMO integration, ML, and deep learning, and metaheuristic algorithms. However, several critical challenges remain to be addressed despite the improvements. Consequently, related research and the search for innovations must be continued.

Regarding the power allocation challenge, resource control in VLC-NOMA systems has been confirmed through prior research as essential in determining system performance. The reviewed studies revealed the role and efficiency of dynamic power distribution and the utilization of sophisticated algorithms, including MFOPA and security-aware water filling. However, some deficiencies persist, especially about real-time adaptation and scalability in multiuser, multicell environments. The major challenge is how to control power sharing among several simultaneous users and ensure that QoS and security are not compromised. A possible solution to the problem of responding to a changing environment may be the application of a sophisticated mixed approach that consists of a heuristic-based algorithm in conjunction with ML to control the power distribution during experiments.

Regarding the MIMO challenge, substantial gains in terms of spectral efficiency can be achieved if MIMO technology is incorporated into NOMA-VLC systems. However, MIMO is difficult to implement in contexts with high mobile user density and correlated channels. Research has also shown that techniques and new algorithms, including RSMA, can null interference and provide excellent results. However, system complexity and its trade-off relationship with performance efficiency continue to present a challenge. Future systems may employ low-complexity MIMO architectures with AI to predict the directions of deep learning-based beamforming and interferences.

About the ML challenge, in different facets of VLC systems, ML has been proven to be useful in reducing noise, modeling channels, and even managing resources. However, the utilization of ML is always challenging because of the need for a huge amount of data and the time-consuming process of training intricate models. The difficulty lies in creating models for ML that can function in a real-time environment and can easily alter their behavior depending on the environment. A promising development is in federated learning, in which model training takes place across decentralized devices with local data, thus minimizing the need for data aggregation and central processing.

Regarding the deep learning challenge, perfect SIC and resource allocation create problems in VLC-NOMA systems, for which deep learning provides powerful and effective solutions. Analysis of the reviewed studies also showed that with the help of deep learning algorithms, such as CNN and DQN, system performance could be improved. However, the high computational requirements of deep learning models and the problem of overfitting within small datasets are pose difficulties. To counter these issues, lightweight deep learning models that are ready for edge computation may be designed to achieve high accuracy with a minimal computation burden.

Furthermore, evidence indicates that metaheuristic algorithms, such as PSO and HHO, can be used to solve complex issues, including user pairing, power allocation, and UAV positioning, in VLC-NOMA systems. However, although these algorithms are effective for optimization, they need numerous iterations to converge; in some cases, they result in high computational costs. Moreover, these algorithms can be highly sensitive to the parameters used. Future work should be directed toward new-generation metaheuristic-based hybrid methodologies that can optimize by combining the features of multiple algorithms and use intelligent schema adaptations to improve the rate and reliability of convergence.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

Figure (2) shows the quantitative distribution of published papers from 2019–2024. Analysis reveals a yearly variation in the number of papers published, including a high point in 2023 with 8 papers and a low point in 2024 with only 1 paper as of this writing. The year 2021 produced the least papers (i.e., 3), so we can assume that the activity of researchers during this year decreased, which may be explained by external factors, such as the COVID-19 pandemic. The smoothing of the peaks and troughs indicates that research activity has resumed, especially in 2023.

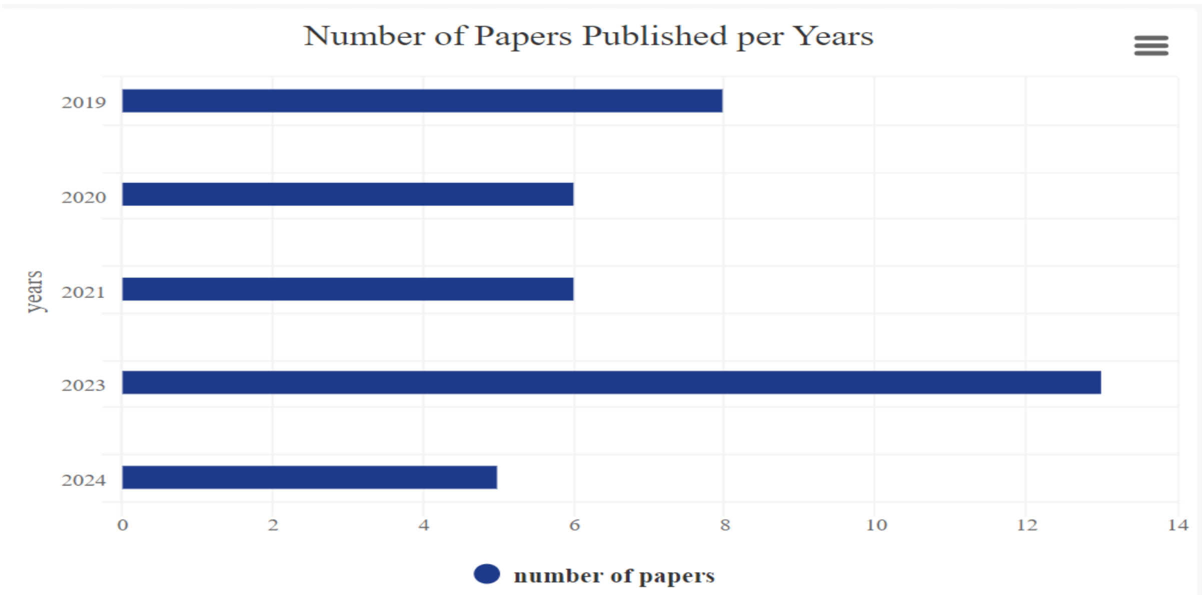

Figure 2. Number of papers published per year

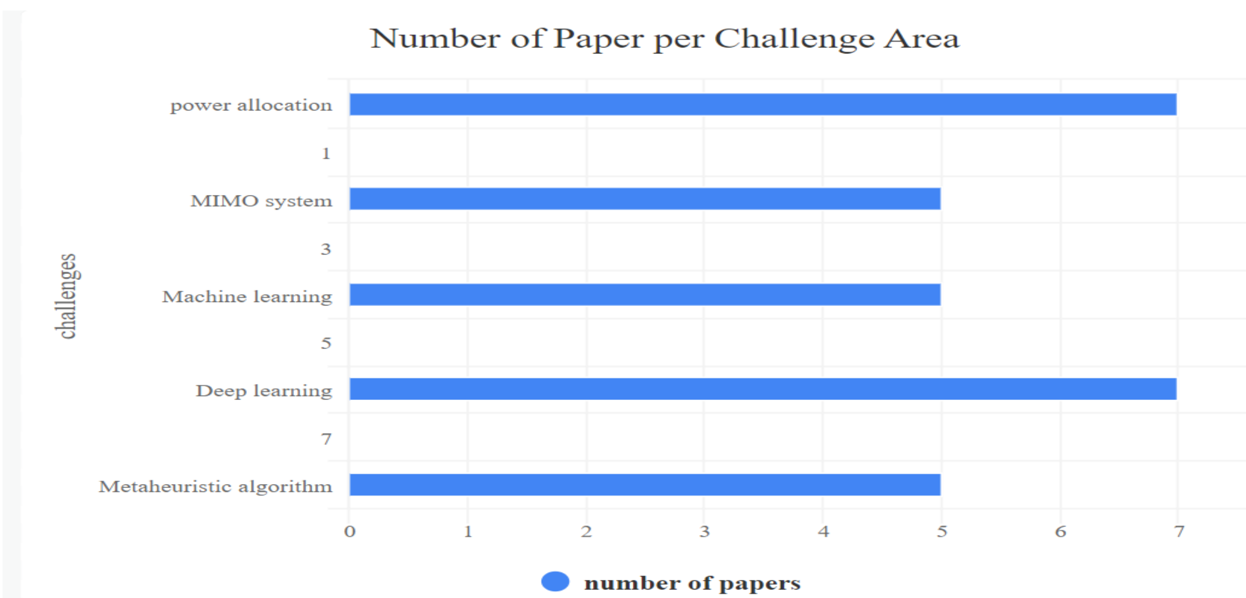

Figure 3. Number of papers by challenge area

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

Figure (3) displays all the papers, and the research challenges encountered. They are classified into different bars in the figure. The subfield of “deep learning” has 9 papers, indicating its increasing importance and utilization in VLC-NOMA systems. The second most represented category is “power allocation” with 7 papers, proving the importance of this factor in system performance enhancement. The most searched for terms in this context are “MIMO VLC NOMA” and “metaheuristic algorithms,” both of which appear in 6 papers. The least searched for term in this context is “machine learning,” which features in only 4 papers. This distribution infers that even though deep learning is an extensively analyzed topic, power allocation and MIMO integration are crucial issues in the development of the field.

The progress in this area is well demonstrated through the discussion of the difficulties and the assessment of different sophisticated approaches in VLC-NOMA systems. However, this study points out that integration and highly adaptive strategies are needed to build on the improvements achieved and realize enhanced performance within the framework. To meet these needs, proposed systems could apply federated learning, which aims to split the computational task among the devices. This approach will reduce the reliance on the central processing of data, thus enhancing real-time operation flexibility and decreasing the response time. Incorporating lightweight deep learning models tailored for edge computing can guarantee high efficiency even in conditions with restricted hardware resources which are typical in numerous scenarios. Furthermore, by integrating metaheuristic hybrid algorithms with independent tunable parameter adjustments, the system can optimally address the problems of power control and user pairing in real time without compromising time consumption. Such algorithms can help the system adapt to inevitable fluctuations in network connectivity and user demands for outcome production.

The following text shows some of the distinct properties of metaheuristic algorithms that make them applicable for solving most of the time-complex optimization problems in VLC-NOMA systems. Such algorithms, including PSO and HHO, are intended to search vast solution spaces and therefore have applications in optimizing complex problems, which conventional approaches may not be able to solve successfully. They are scalable and can be smoothly applied to a broad spectrum of issues without dramatic augmentation, which benefits the process of solving nonconvex, NP-hard issues typical in power allocation, user pairing, and UAV placement. Moreover, metaheuristic algorithms are mostly parallel, and this increases their capability, especially in large systems.

ML and data analysis are processed in real time and involve an extensive toolset for making decisions and forecasts when necessary. Notably, in the case of VLC-NOMA systems, ML algorithms can be trained to review previous data and make necessary adjustments in the parameters, including power levels or channel conditions. This capability makes allows the algorithms to fine tune the system and achieve an enhanced SNR ratio, improved BER, and increased overall system efficiency. Moreover, ML can be combined with deep learning to deal with the various sophisticated patterns and interconnections within the data in question to enhance the general decision-making process. Given the highly interconnected nature of metaheuristic algorithms and ML, the proposed system can be a highly flexible, scalable, adaptive solution to the problems encountered by VLC-NOMA systems. Using this kind of approach will guarantee the versatility of the system, allowing the system to run in almost any environment. It can serve as the foundation of future advanced wireless networks with improved reliability, enhanced performance, and increased adaptability to current-day applications.

The above-mentioned challenges were identified through this review. They reveal the need for additional enhanced solutions that encompass integration and adaptability for enhancing VLC-NOMA systems. For instance, a system that uses federated learning, which can distribute calculated tasks on different devices, could be developed to minimize the use of centralized approaches and promote real-time adaptability. This development will help in the design of lightweight models that focus on edge computing to guarantee high performance in such a scenario. In addition, a system that integrates point hybrid metaheuristic algorithms with adaptive parameter control could be developed to simultaneously address optimization challenges, such as power control and user pairing, in almost real time. By integrating metaheuristic algorithms and ML, such a system can be highly flexible, scalable, and adaptive to the issues encountered in VLC-NOMA systems. This method can ensure that the system suits various situations prior to the development of other reliable wireless networks that can support contemporary applications.

7. Future direction

This study highlights the potential of using ML techniques in enhancing VLC-NOMA systems and identifies the critical areas for future exploration. To address scalability challenges, future research should investigate federated learning frameworks and hybrid metaheuristic approaches for dynamic optimization in multiuser environments. The integration of edge AI can enable real-time inference, particularly in resource-constrained scenarios, such as IoT and vehicular communication. Experimental validation of ML-based VLC-NOMA solutions under real-world conditions is essential to ensure their practical feasibility. Moreover, the development of lightweight energy-efficient models, alongside robust security frameworks, is pivotal for sustainable and reliable deployment in 6G networks.

DOI: https://doi.org/10.54216/FPA.200104
Received: January 17, 2025 Revised: March 01, 2025 Accepted: April 07, 2025

8. Conclusion

The combination of NOMA and VLC represents a straightforward approach to how network capacity, user fairness, and overall performance can be improved for next generation 6G systems. However, this combination creates critical issues, such as nonlinear distortions, error propagation, and complexity of signal processing, each of which requires efficient, creative solutions. As revealed by this systematic review, ML and deep learning algorithms are revolutionary in dealing with these challenges. They can considerably enhance channel estimation, signal processing, and system security. The effectiveness of ML and deep learning models of metaheuristic algorithms in resource allocation, power distribution, and user association and distribution results in a substantial enhancement of system efficiency and reliability.

However, this study shows that several issues remain unexplored and resolving them can be the focus of future studies. To keep up with ever-evolving channel circumstances and user needs, future research should concentrate on developing strong ML algorithms. Feasibility assessments of ML-based solutions that have been presented within the framework of practical VLC-NOMA systems should be conducted to ensure theoretical development. Furthermore, related research should concentrate on experimental outcomes. The integration of VLC, NOMA, and ML is promising and can substantially affect the future development of wireless communication, especially 6G wireless networks. These technologies are expected to help in meeting the growing need for high-speed, dependable, power-conscious communication systems as the research in this field progresses continuously.

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