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Performance Evaluation of Downlink NOMA-Based VLC System with Different Modulation Techniques

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Abstract: Visible Light Communication (VLC) has emerged as an innovative networking technique post-5G, leveraging its expansive license-free spectrum. However, the main challenge remains the narrow modulation bandwidth of light sources. To address this, Non-Orthogonal Multiple Access (NOMA) has been proposed as a successful method to significantly enhance spectrum efficiency in downlink VLC systems. This study evaluates the error performance of a NOMA-based downlink VLC system using high-order modulation schemes, specifically M-Quadrature Amplitude Modulation (M-QAM). MATLAB simulations are employed to assess the Symbol Error Rate (SER) for two users. The study investigates how changing the modulation order impacts SER for both users and examines the influence of Power Allocation (PA) coefficients. Results indicate that increasing the modulation order affects SER differently for each user. Moreover, adjusting the PA coefficient for the farther user can improve performance at higher signal to noise ratio (SNR) but shows limited effectiveness at lower SNRs. Also our work investigates downlink NOMA-Based VLC System, concentrating on how different modulation techniques affect the system performance.

Keywords: visible light communication (VLC), non-orthogonal multiple access (NOMA), symbol error rate (SER) , power allocation (PA).

1. Introduction

VLC represents a potentially disruptive technology that could introduce new applications for mobile wireless devices [1]. Light-emitting diodes (LEDs) have become integral to indoor lighting systems due to the rapid advancements in solid-state lighting (SSL) technology [2]. VLC utilizes a vast, unlicensed spectrum ranging from 430 to 790 THz, offering accessibility, higher energy efficiency, and other benefits. These advantages position VLC as a potential candidate for 5G and future networks. Recently, VLC has been adopted in various applications such as WLAN, LiFi, medical devices, localization systems, underwater communication, among others [3]. This has led to the emergence of two primary multiple access (MA) approaches: orthogonal multiple access (OMA) and NOMA.

In OMA, to mitigate MA interference, each user utilizes orthogonal communication resources within specific time intervals, frequency bands, or codes. Earlier network generations employed OMA techniques such as Orthogonal Frequency Division Multiple Access (OFDMA). On the other hand, NOMA achieves high spectrum efficiency by allowing multiple users to utilize non-orthogonal resources simultaneously, albeit with some tolerance for MA interference at receivers [4].

In NOMA, signals from both users are multiplexed to transmit simultaneously, enabling the weaker user with narrower bandwidth to receive a larger portion of power. Meanwhile, the user with limited bandwidth can access spectrum resources. This arrangement enhances the overall throughput of the system [5]. Superposition coding (SC) is utilized in NOMA near the transmitter to multiplex signals from multiple users, employing varying power levels determined by channel state information (CSI) for each user. Specifically, users with better channel conditions receive lower PAs, while those with poorer conditions receive higher PAs. At the receiver, decoding is achieved through successive interference cancellation (SIC), a method capable of detecting multiple users simultaneously [6].

Indoor VLC, which employs intensity modulation and direct detection (IM/DD), faces challenges with traditional QAM due to the production of bipolar and complex-valued symbols. To address this, Orthogonal Frequency Division Multiplexing (OFDM) is used, which generates real-valued time-domain signals through the exploitation of Hermitian symmetry. Techniques like asymmetric clipping (ACO-OFDM) or direct current modulation (DCO-OFDM) with a positive direct current (DC) are also employed to achieve unipolar time-domain signals, enhancing the feasibility of indoor VLC [7].

In our paper, the SER analysis of downlink VLC system with NOMA by M-QAM is presented. The paper discusses the impact of altering the value of the PA coefficient using SER. Also the effect of different modulation techniques on NOMA-Based VLC System is demonstrated. The remaining portions of this paper are structured as follows: Related work is described in Section 2. System model is demonstrated in Section 3. Section 4 presented SER analysis. The discussion and numerical findings are then covered in section 5. Section 6 described the conclusion.

Authors in [8] examines the performance of a power-domain nonorthogonal multiple access (PD-NOMA)-based visible light communication (VLC) system. It primarily looks into indoor and outdoor IoT network environments using different VLC system channel models. This study initially examines the distribution function of the received signals and the system noise in real-world settings in order to improve the analysis of the PD-NOMA-based VLC system performance that is already available. Second, it deduces the theoretical BER formulas for both the indoor and outdoor settings and investigates how ambient noise affects the system's bit error rate (BER) under indoor Gaussian channels.

Lastly, theoretical symbol error rate (SER) formulas are obtained for the indoor and outdoor three-device PD-NOMA-VLC system. The theoretical analysis and simulation results are well matched by numerical simulations, especially under high signal-to-noise ratio (SNR) scenarios.

The work in [9] looks at the power-domain NOMA - VLC system with the optical intelligent reflecting surface (OIRS) assistance, where the sum rate that can be achieved is increased by maximizing the OIRS reflection matrix. By defining the OIRS qualities in terms of an association matrix, transforms the OIRS optimization issue into a binary programming problem, and then iteratively optimizes the OIRS passive beam forming using the suggested low-complexity technique. The OIRS increases the NOMA-based VLC system's possible sum rate, according to simulation results, and the suggested algorithm outperforms alternative baseline systems.

Authors in [10] analyze numerous NOMA-enabled VLC systems and attempts to provide firsthand knowledge of the significance of both NOMA and VLC. Briefly describes the capabilities and promise of VLC systems based on NOMA. Furthermore, describes how these systems can be integrated with a number of cutting-edge technologies, including unmanned aerial vehicles (UAVs), multiple-input multiple-output (MIMO), intelligent reflecting surfaces (IRS), and orthogonal frequency division multiplexing (OFDM). Moreover, addresses the function of physical layer security (PLS) and machine learning (ML) technologies in the context of NOMA-based hybrid RF/VLC networks, identifies also a number of important and varied technological challenges that NOMA-based VLC systems face.

Authors in [11], offers a theoretical framework for analyzing the short-packet communication (SPC) performance in a downlink VLC system that uses two single-photodiode users and one light emitting diode (LED) for communication. The system operates under NOMA mode. The Gaussian-Chebyshev quadrature approach approximates the analytical expression of the block error rate (BLER), from which the latency, throughput, and reliability expressions are derived. Moreover, in order to enhance the SPC-NOMA VLC system's total throughput, simultaneously optimizes transmission rates and PA coefficients.

Authors in [12], examines the functionality of a visible light communication (VLC) system that is based on downlink non-orthogonal multiple access (NOMA). We take into consideration that a binary Poisson point (BPP) Process is used to find the users at random. Novel closed-form formulas for the bit error ratio (BER) and ergodic sum rate are derived in order to assess the performance of the system under consideration. The BER analysis additionally accounts for the effect of an error resulting from successive interference cancellation (SIC). The results collected in relation to various system parameters are crucial in offering insightful information about the functionality of the system.

The work in [13] provides a thorough information about user paired and PA methods for VLC systems based on NOMA. Regarding VLC systems using NOMA, many different user pairing strategies and PA techniques are presented. There has been discussion of a performance-based analysis indicators, including sum rate, bit error rate (BER), outage probability, etc.

The previous work summarized in table 1.

	Used Methods	Ref.	Simulation Tool	Contribution
1	PD-NOMA	8	numerical simulations matlab	improve the analysis of the PD-NOMA-based VLC system performance
2	optical intelligent reflecting surface (OIRS) assistance	9	matlab	increases the NOMA-based VLC system's possible sum rate
3	NOMA-based VLC systems with the integration of several emerging technologies such as IRS, OFDM, UAV, ML, PLS, MIMO, etc	10	matlab	Provide a comprehensive review of NOMA schemes for VLC systems, which contains an extensive coverage of the existing literature
4	short-packet communication (SPC) in downlink vlc	11	Monte Carlo simulations	the short-packet communication (SPC) NOMA VLC system provides higher reliability and lower latency in comparison to the LPC-NOMA VLC system
5	binary Poisson point (BPP) Process	12	matlab	find the users at random location
6	near-far pairing, uniform channel gain difference (UCGD) pairing, hybrid pairing, divide-and-next largest gain user pairing (D-NLUPA), vertical user pairing, virtual user pairing, etc.	13	matlab	A review of various user pairing and power allocation techniques for NOMA-based VLC systems .

2. SYSTEM MODEL

This paper explores a downlink VLC configuration where a single LED is installed in a typical indoor environment. The LED simultaneously serves two users by adjusting the light intensity based on information obtained via a power line communications backbone network. This setup allows the LED to function both as a light source and a communication transmitter. Each user is assumed to have a photo-detector (PD) that performs Direct Detection (DD) to extract the received optical carrier signal. Higher-order modulation techniques such as QAM are employed to enhance the spectral efficiency of NOMA significantly.

NOMA is a successful method for delivering significant performance improvements in communication systems. A dual user indoor VLC system for downlink employing IM/DD is being considered. It employs a PD to be the receiver and just one LED to be the transmitter. for each user. According to the channel quality, users are listed starting with |h2| to |h1| [15]. Substantial channel gain user named User 2, considered to be a near user, and User 1, who has a low gain of channel, is regarded as a far user. The using indicates the NOMA concept, In terms of PA coefficients, near users have (1-P) and far users have P, respectively, where P is the PA coefficient.

A VLC downlink system based on NOMA is displayed with two users within the block diagram in Figure 1. The user data is mapped using M_k-QAM. Each user's signal receives a certain amount of power. Next, signals are combined, and then ACO-OFDM is used in our study to prevent the introduction of extra noise brought on by negative values in DCO-OFDM or any O-OFDM with DC bias being clipped. Then the electrical signal is transformed into an optical signal by the LED.

The signal will be decoded by the receiver for the first user using the signal that was received, whereas considering signal from a second user like noise. SIC can be used to decode a signal from a second user [7].

We will calculate the user's SER for any M_F and M_S where M_F and M_S are the number of constellation points for the first and second users. We assume that M_F and M_S both are equal to 16. We will then generalize the result. The overlay 256 symbols will make up the constellation of the signal whenever a 16-QAM constellation is shared by each user. Let FU and SU represent the symbols used by the first and second users, respectively. Let P and 1-P are the user's respective PA coefficients.

$$\mathrm{FU} = A_{IF}\mathcal{E}_F\sqrt{PE_S} + jA_{QF}\mathcal{E}_F\sqrt{PE_S} \qquad (1)$$

$$\mathrm{SU} = A_{IS}\mathcal{E}_S\sqrt{(1-P)E_S} + jA_{QS}\mathcal{E}_S\sqrt{(1-P)E_S} \qquad (2)$$

Where A_I and A_Q are, respectively, the in-phase and quadrature alphabets , $\mathcal{E}$ is a normalization factor.

$$\mathcal{E}_F = (\ 2/3\ (M_F - 1))^{-1} \qquad (3)$$

$$\mathcal{E}_S = (\ 2/3\ (M_S - 1))^{-1} \qquad (4)$$

The first user's SER (SER_F) is given as [7]:

$$SER_F = \frac{4}{M_F M_S}\sum_{i=1}^{\sqrt{M_S}}\sum_{j=1}^{\sqrt{M_S}}\Big((M_F - \sqrt{M_F})\mathcal{Q}\Big(\gamma_F\big(\mathcal{E}_F\sqrt{P} + A_i\mathcal{E}_S\sqrt{(1-P)}\big)\Big) - (M_F - 2\sqrt{M_F} + 1)\ \mathcal{Q}(\gamma_F\ (\mathcal{E}_F\sqrt{P} + A_i\mathcal{E}_S\sqrt{(1-P)})) * \mathcal{Q}(\gamma_F(\mathcal{E}_F\sqrt{P} + A_j\mathcal{E}_S\sqrt{(1-P)}) \qquad (5)$$

SER of the second user (SER_S) is given as:

$$SER_S = (1 - SER_{S\to F}).SER_{S\to S} + SER_{S\to F} \qquad (6)$$

Where $SER_{S\to F}$ acts as the SER that handles detection's second user of the first-user signal and is given as:

$$SER_{S\to F} = \frac{4}{M_F M_S}\sum_{i=1}^{\sqrt{M_S}}\sum_{j=1}^{\sqrt{M_S}}\Big((M_F - \sqrt{M_F})\mathcal{Q}\Big(\gamma_S\big(\mathcal{E}_F\sqrt{P} + A_i\mathcal{E}_S\sqrt{(1-P)}\big)\Big) - (M_F - 2\sqrt{M_F} + 1)\mathcal{Q}(\gamma_S(\mathcal{E}_F\sqrt{P} + A_i\mathcal{E}_S\sqrt{(1-P)})) * \mathcal{Q}(\gamma_S(\mathcal{E}_F\sqrt{P} + A_j\mathcal{E}_S\sqrt{(1-P)}\ )) \qquad (7)$$

After correctly recognizing and removing the first-user signal, $SER_{S\to S}$ will be the second user's SER in the recognition of its own signal and is given as [7]:

$$SER_{S\to S} = 4(1 - \frac{1}{\sqrt{M_S}})\ \mathcal{Q}(\gamma_S\mathcal{E}_S\sqrt{(1-P)}\ ) - 4\ (1 - \frac{2}{\sqrt{M_S}} + \frac{1}{M_S})\ \mathcal{Q}\ (\gamma_S\mathcal{E}_S\sqrt{(1-P)}\ )^2 \qquad (8)$$

$$\text{With } \gamma_k = \sqrt{2g_k^2E_s/N_O} \qquad (9)$$

Es denotes the overall average energy.

The flow chart that describes our system is indicated in figure 2.

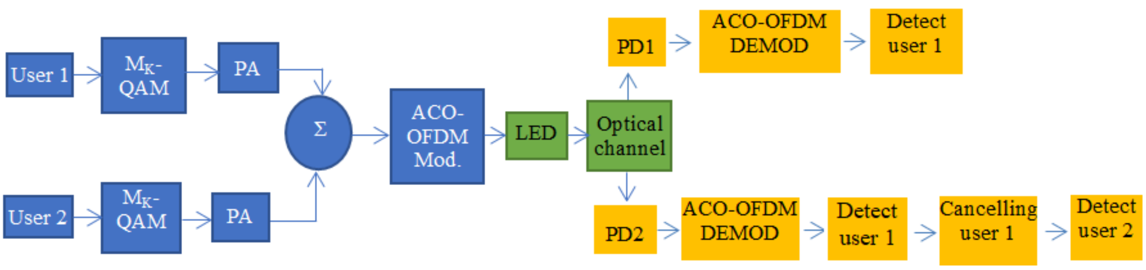

Figure 1: block diagram for a VLC system with ACO-OFDM that supports two users of NOMA.

3. NUMERICAL RESULTS AND DISCUSSION

The theoretical and simulated values of SER due to first user in comparison to second user are shown in figures 3, 4, and 5 for different modulation orders for second user while the first user uses 4 - QAM, also users are given varying amounts of power in each situation. The theoretical and simulated SER of the first user are denoted by ser_F, ser_{Fs} respectively. SER of the second user, both theoretically and simulated are denoted by ser_S, ser_{Ss} respectively.

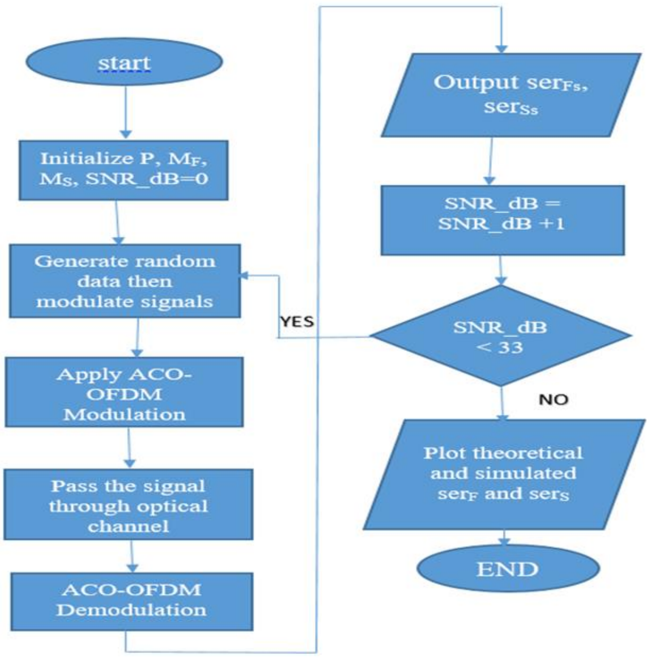

Figure 2: System Model Flow Chart

Figure 3 shows the first user's SER compared to the second user for different values of SNR at P = 0.85, M_F = 4 and M_S = (4, 16, 64). As the SNR rises, the SER falls, and by increasing the second user's modulation order the SER increases.

The first user's SER compared to second user for different values of SNR at P =0.7619 is presented in figure 4. By decreasing PA for first user, SER for first user increases.

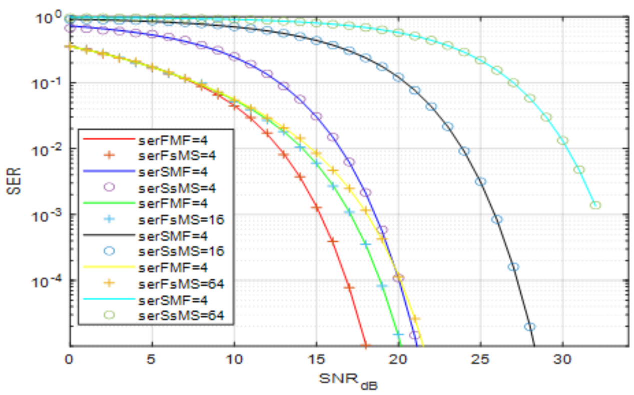

Figure 3: The first user's SER compared to second user for different values of SNR. MF =4, MS = (4, 16.64) and P=0.85.

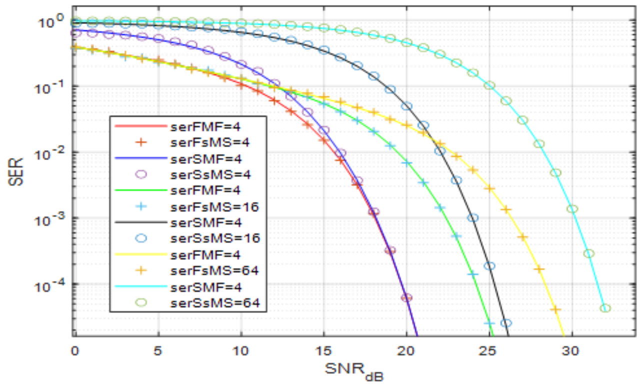

Figure 4: The first user's SER compared to second user for different values of SNR. MF = 4, MS = (4, 16, 64), and P = 0.7619.

Figure 5 shows the first user's SER compared to second user for different values of SNR at P=0.643. Given this, the second user symbols' minimum distance in the constellation diagram increases when P = 0.643.

The constellation that is superimposed, though, begins to have some of its symbols overlap. It is challenging to appropriately decode the symbols for the first user in this situation. In the above examples P > (1-P), however the constellation that is superimposed has some symbols that overlap. The requirement P > (1-P) is therefore required but insufficient to guarantee successful decoding. There is an optimum value for PA factor for the second user to guarantee successful decoding.

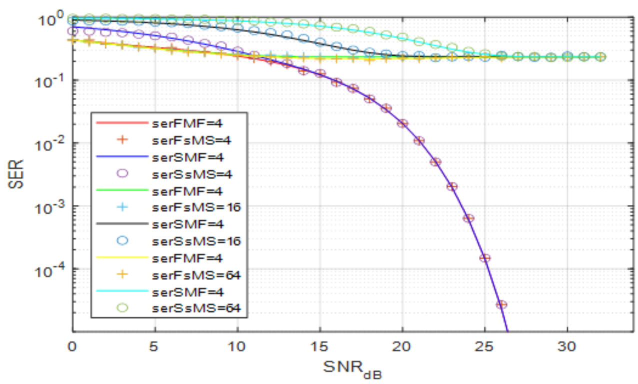

Figure 5: The first user's SER compared to second user for different values of SNR. MF = 4, MS = (4, 16, 64), and P = 0.64286.

Figures 6 and 7 illustrate how the performance of the NOMA-VLC system is affected by the PA coefficient. We consider that when no power control exists (P=0.5) $M_F = M_S$ = 4, the findings indicate that SER has increased.

Figure 6 illustrates how the performance of the NOMA-VLC system is affected by the PA coefficient when $M_F = M_S = 4$.

When there is no power control (P=0.5), $M_F = M_S = 4$, the results show that the SER increases. The SER value is better for higher values of SNR as shown in figure 6. By increasing PA coefficient (P=0.85, 0.86, 0.87, 0.88, 0.89, 0.9) M_F=4, M_S=4, the SER of the first user decreases. The figure reveals that when P grows, performance with errors of a far user advances. The rationale for the far user's increased performance is that when P rises, more power is allocated to it, easily offsetting the impact of the channel's poor state.

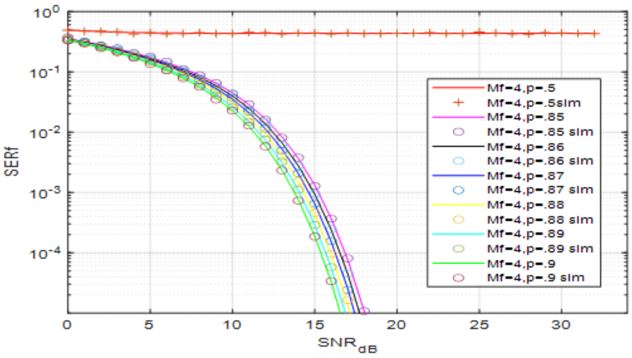

Figure 6: SER of the first user with SNR for different values of P and MF = 4 and MS = 4.

Figure 7 illustrates how the performance of the NOMA-VLC system is affected by PA coefficient when M_F= 16, M_S=4. By increasing PA coefficient (P=0.85, 0.86, 0.87, 0.88, 0.89, 0.9) M_F=16, M_S=4, the SER of the first user decreases and The SER value is better for higher values of SNR as shown in figure 7. The best performance occurs when M_F = 16, M_S= 4 and the value of P = 0.9.

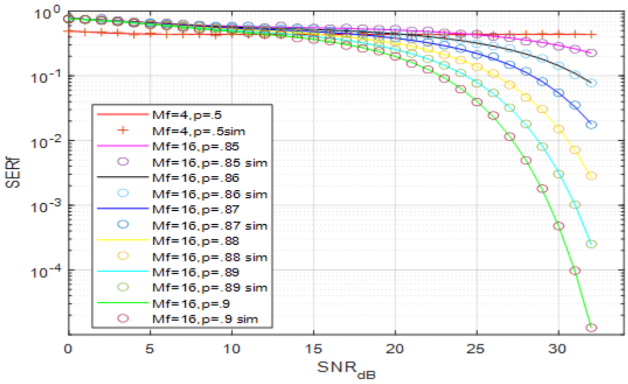

Figure 7: SER of the first user with SNR for different values of P and MF = 16 and MS = 4.

From figures 6 ,7 the best performance occurs when M_F = 4, M_S = 4 and the value of P = 0.9. Next value when M_F=16, M_S=4 and the value of P = 0.9.

The simulated SER of the first user with SNR for different values of P and M_F = 2 and M_S = 2 is shown in figure 8 using BPSK modulation.

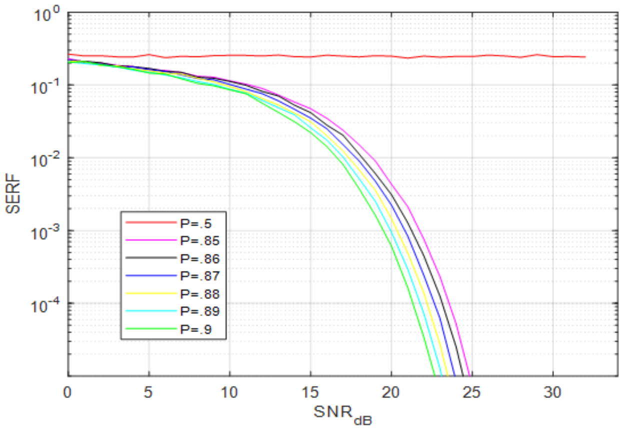

Figure 8: The first user's SER with SNR for different values of P and MF = 2 and MS = 2.

The simulated SER of the first user with SNR for different values of P and M_F = 2 and M_S = 2 is shown in figure 9 using PAM modulation.

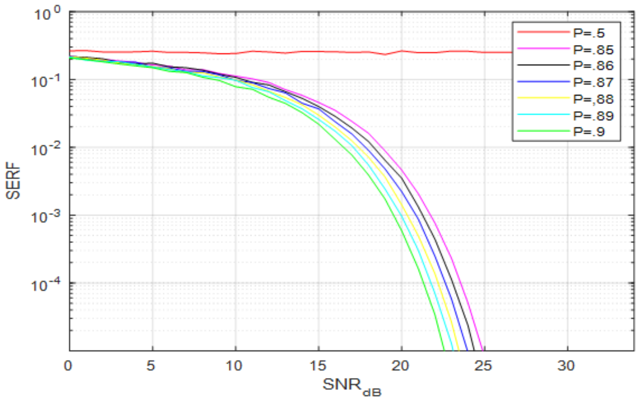

Figure 9: The first user's SER with SNR for different values of P and MF = 2and MS = 2.

From figures 8 and 9, we consider that when there is no power control (P=0.5), M_F = M_S = 2, the results show that the SER value is maximum. By increasing PA coefficient (P=0.85, 0.86, 0.87, 0.88, 0.89, 0.9) M_F = M_S =2, the SER of the first user decreases. The figure reveals that when P grows, performance with errors of a far user advances. The rationale for the far user's increased performance is that when P rises, more power is allocated to it, easily offsetting the impact of the channel's poor state.

4. CONCLUSION

In this study we have worked on an indoor VLC system. The system's performance was simulated for different PA values, and we discussed the comparison of the SER performance of two users with different modulation orders. PA expressions are validated by the simulation results, which agree with the theoretical result. It is found that when the modulation order increases, the SER increases. The requirement P > (1-P) is required but not sufficient to guarantee successful decoding. The best performance is found at P = 0.9.

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