Space Shift Keying Modulation in Non-Orthogonal Multiple Access Hybrid Visible Light Communication Systems

(Invited Paper)

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***Abstract*—Visible light communication (VLC) is considered a breakthrough wireless communication technology that has been proven capable of achieving very high data rates. This is a key advantage in indoor communication scenarios, since the vast majority of wireless traffic is witnessed in indoor communications. In every wireless system, the trade-off between achievable throughput, transmit signal power and corresponding error rate performance is largely dependent upon the considered modulation format. This is also the case in VLC systems, which are typically characterized by stringent performance requirements. Motivated by this, in the present contribution we introduce the space shift keying (SSK) modulation scheme in the context of non-orthogonal-multiple-access (NOMA) communications, which have been shown to be a performance enhancer of indoor based VLC systems. Based on this, all network users in the considered set up receive the same superimposed signal of all NOMA users, which is transmitted from the activated transmitters corresponding to the multiplexed SSK users information. Based on this and assuming a unique maximum likelihood detection, we quantify the system performance in terms of the corresponding bit error rate (BER) performance at each receiver. This analysis leads to the development of useful insights of theoretical and practical interest, which are expected to be useful in the effective design, implementation and deployment of SSK in NOMA based VLC systems.**

I. Introduction

Visible Light Communication (VLC) is a prospective technique that can significantly increase the efficiency of wireless data transmission. However, a fundamental drawback lies at the core of this technique, that the data transmission efficiency depends on the light source. Hence, different techniques in the literature were proposed to increase the spectral efficiency, including different modulation schemes, [1] and the references therein. Recalling that sources with low modulation bandwidth impose a crucial limitation on the achievable data transmission rate, modulation schemes such as the space shift keying (SSK) can be rather effective and efficient. In this modulation scheme, the information is transmitted by index modulation, which is implemented in optical space shift keying (OSSK) and offers enhanced data rate [1]. An illustration of the OSSK modulation scheme is illustrated in Figure 1 for the indicative case of four light emitting diodes (LEDs). The corresponding functionality in this scheme is index-based, where, for example, the information, i.e. the index, 01 refers to the second LED meaning that the second LED is active.

Importantly, the distinct characteristic of spatial modulation is that it makes use of the spatial location of the light emitting diode, which offers a supplementary degree of freedom in data modulation leading to a significantly increased efficiency. Based on this, considerable research efforts have been devoted to quantifying the capabilities and shortcomings of SSK scheme in optical wireless communications, aiming at achieving enhanced efficiency at moderate, if not simple, complexity. To that end, the authors in [2] addressed the performance of SSK in VLC systems, whereas the direct-code space shift keying (DC-SSK) modulation scheme was investigated in [3].

It is recalled that multiple-input-multiple-output (MIMO) technology has been applied extensively in emerging wireless technologies in order to increase the capacity of modern communication systems that are often characterized by stringent quality of service requirements. Motivated by this, MIMO was addressed in the context of VLC systems in [2], [4], [5], which, as expected, showed and enhanced spectral efficiency. The authors in [6] proposed a radio frequency (RF) based scheme that exhibits favorable performance based on super positioning of two schemes. In the context of optical wireless communications, MIMO in VLC system was addressed in [2] and in [7], offering useful insights of theoretical and practical importance in indoor communication scenarios.

It is also recalled here that non-orthogonal multiple access (NOMA) is a relatively recently proposed multiple access scheme that has been proven capable of providing increased data rates in demanding wireless scenarios [8], and the references therein. The distinct characteristic of NOMA is that

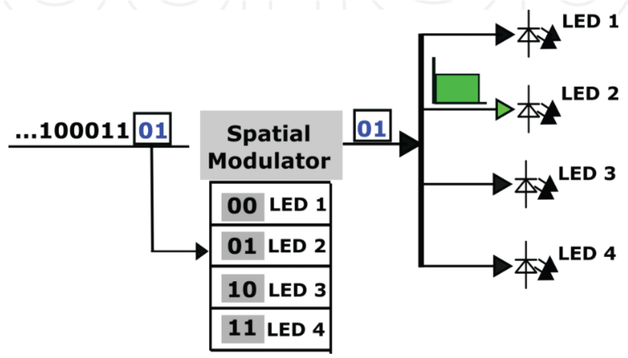

Fig. 1. Illustration of OSSK for four LEDs [11]

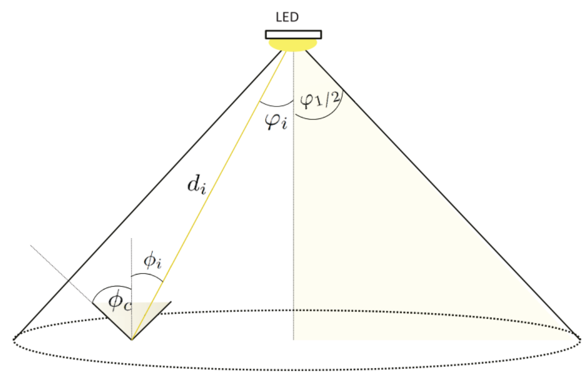

Fig. 2. VLC Channel

the signals of the different involved users are superimposed in the power domain, which is realized by allocating different power levels to each user based on the channel conditions [8]. Specifically, unlike the classical *water-filling* approach, the highest power level is allocated to the channel with the most severe fading conditions and, conversely, the least power is allocated to the channel with the most favorable fading conditions. Therefore, all users can practically utilize simultaneously the entire bandwidth through power domain superposition coding at the transmitter side, while successive interference cancellation (SIC) is employed at the receivers in order to mitigate the corresponding resulting interference. In addition, this multiple access is more suitable for the case of different communication channels, which is practically the case in realistic communication scenarios. Finally, it has been shown that it overall exhibits a better performance, particularly in case of high signal-to-noise ratio (SNR) scenarios [9], [10].

Motivated by the above, the present contribution is concerned with the analysis of SSK modulation in NOMA based communications in the context of VLC systems. In this context, maximum-likelihood (ML) based decoder at the SSK receiver is introduced, which is based exploiting of the pre-knowledge of the superimposed NOMA signals in order to successfully detect the data symbols and extract the corresponding information at the SSK based receivers. In this context, it is shown that that additionally to the higher capacity achieved due to the adoption of NOMA, the proposed system configuration achieves a sufficient performance in terms of the corresponding error rate. Importantly, this does not comes at an increased complexity cost, which is typically the case in demanding emerging communication technologies.

The remainder of this work is organized as follows: the proposed system configuration of SSK modulation with a NOMA based VLC system model is demonstrated in Section II, where the channel model is also explained. The corresponding results and their analysis are demonstrated in Section III along with the development of interesting insights and useful discussions. Finally, the work is concluded with closing remarks in Section IV.

II. System Model

We consider a multiple-LED downlink transmitting in a regular indoor setting. The considered LEDs are of dual purpose as they are expected to perform both illumination and communication functionalities serving U_1 SSK user and $U_2, U_3, \cdots, U_G$ NOMA users. Moreover, all users in both systems are assumed to be able to perform a direct detection using the photo-detector installed in each user device obtaining the transmitted signal from the received carrier. This is essentially realized using unipolar on-off keying (OOK) modulation. Space Shift Keying modulation is utilized for the transmitted signal to all users. In this context, one LED is active at the time of symbol transmission, hence the information is modulated spatially. The LED transmitter adopts SSK modulation for the index corresponding to users U_1, and using fixed power allocation FPA for exploiting the super-positioning on the symbol corresponding to users $U_2, U_3, \cdots, U_G$.

A. VLC Channel

In indoor VLC settings, as illustrated in Firgure 2, multipath delays caused by diffuse refractions and reflections are typically negligible based on the line of sight (LOS) [8] considered in this communication set up [12]. Based on this, the representation of the channel between the user and the corresponding LED can be represented as follows:

$$h_i = \begin{cases} \frac{A_i}{d_i^2} R_o(\varphi_i) T_s \phi_i \cos(\phi_i) g(\phi_i), & 0 \leq \phi_i \leq \phi_c, \\ 0, & \phi_i > \phi_c, \end{cases} \tag{1}$$

where ϕ_i is the angle of incidence with respect to the receiver axis, whereas ϕ_c represents the field of view angle (FOV) of the photodetector. Likewise, T_s is the gain of the optical filer and $g(\phi_i)$ is the gain of the corresponding optical concentrator. Also, A_i denotes the photodetector PD area at the receiver, $i = 1, 2, 3, \cdots, N$, d_i represents the distance between the transmitting LED and the photodetector at the i-th receiver and $R_o(\phi_i)$ is the Lambertian radiant intensity of the transmitting LEDs, which can be expressed as follows:

$$R_o(\phi_i) = \frac{m+1}{2\pi}\cos^m(\varphi_i) \tag{2}$$

where m is the order of the Lambertian emission, with $\phi_{1/2}$, denoting the transmitter semi-angle at half power, namely

$$m = -\frac{\ln(2)}{\ln(\cos(\varphi_{\frac{1}{2}})} \tag{3}$$

with

$$g_{\phi_i} = \begin{cases} \frac{n^2}{\sin^2(\phi_c)}, & 0 \leq \phi_i \leq \phi_c, \\ 0, & \phi_i > \phi_c \end{cases} \tag{4}$$

as also presented in [8].

B. Transmission

It is recalled that in the considered set up we assume that users $U_2, U_3, \cdots, U_G$ are sorted in an ascending order corresponding to their channels, i.e. $(h_1 \leq h_2 \leq ... \leq h_n)$ [8]. Real and non-negative signals $(s_2, ..., s_G)$ each with associated power value $(P_2, ..., P_G)$, respectively, is transmitted from the corresponding LED, where each signal is sent to a specific user. That is that s_i conveys information intended for user U_i. Moreover, the superimposition of G transmitted signals in the power domain is represented as

$$x = \sum_{i=2}^{G} P_i s_i \tag{5}$$

where the total transmitted power from LED is given by

$$P_{\text{LED}} = \sum_{i=2}^{G} P_i. \tag{6}$$

It is noted that the incurred multiuser interference at U_{2+k} can be eliminated with the aid of SIC. Depending on this, for each user to decode its own signal, the receiver at U_{2+k} decodes the previous signals and subtract them from the received total signal successfully in order to remain with the signal intended for itself, while the other signals are treated as noise. In the interest to achieve SIC decoding, fixed power allocation FPA is being facilitated. So, the LED allocates higher power to users with weak channel gains:

$$P_i = \rho P_{i-1} \tag{7}$$

where the power allocation factor ρ is between 0 and 1.

The power associated for the i^{th} sorted user is illustrated in Fig. 3. The user with high channel gain is allocated with lower power to successfully decode the desired signal, while the signals with lower decoding order which are allocated higher power, have been decoded and subtracted beforehand as a first step [8]. To this effect, the received signal is represented as follows

$$y_k = \gamma h_k \sum_{i=2}^{G} P_i s_i + n_k \tag{8}$$

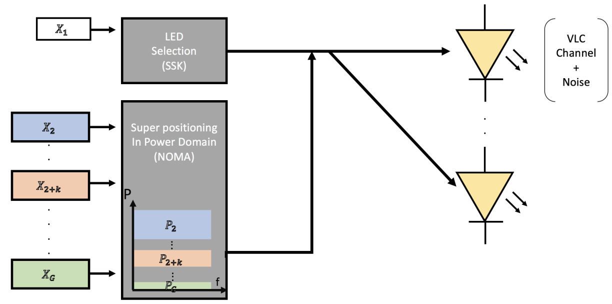

Fig. 3. Transmitter

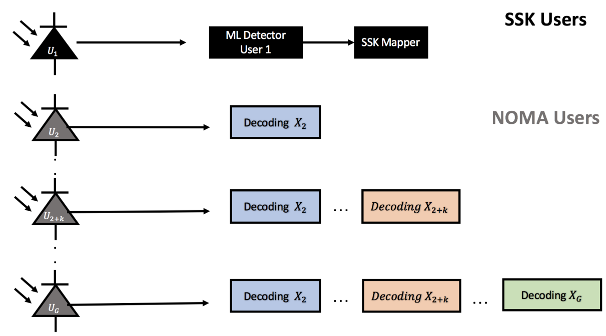

Fig. 4. Receiver

Of note, in order to maintain the best reconstruction at the SSK receiver, a positive signal should be considered,As a result, signals $(s_2, ..., s_G)$ are mapped from 0, 1 to $\frac{1}{3}$ and $\frac{2}{3}$, respectively.

C. Optimal Detector for SSK user

At the SSK receiver end shown in Figure 4, the signal passes through a unifier where the assumption of SSK user having the perfect knowledge of the NOMA signal is considered. Also, each symbol is assumed to be scaled by its inverse. Then, SSK users decode their transmitted symbol by establishing an estimation of the index of the active transmitting LED. This estimation is done by employing the ML detection technique. In SSK receiver end, only the received signal is considered to detect the LED index without the need to decode the NOMA signal. In this context, ML detection with respect to channel gains aspect is considered.

D. Optimal Detector for NOMA users

As already mentioned, the weak user in power NOMA is assigned a greater power using FPA. Therefore, the receiver end first sorted signal is decoded without the need to eliminate and interference due to the high-power factor it has been assigned. Users after that need to eliminate multi-user interference with the aid of the employed SIC. To that end, for the user U_k to decode its dedicated signal successfully, it needs to decode all other users signals (that has lower order (1 to k-1)) and subtract them. This results to the signal for U_k user, while

TABLE I
PARAMETERS USED IN SIMULATION

Description	Notation	Value
LED Power	P_{LED}	0.25 W
Transmitter Semi-angle	φ_i	50 deg
FOV of PDs	ϕ_{ci}	45 deg
Area of PD	A_i	1 cm^2
Refracted Index of PD lens	n	1.5
Gain of optical filter	$T_s\phi_{li}$	1

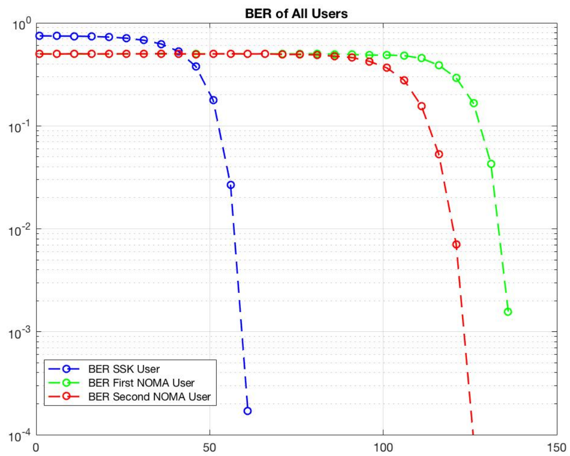

Fig. 5. BER performance of the System

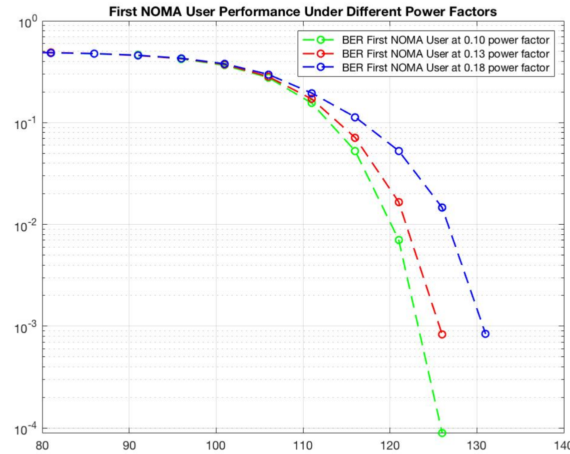

Fig. 6. First NOMA User With Different ρ

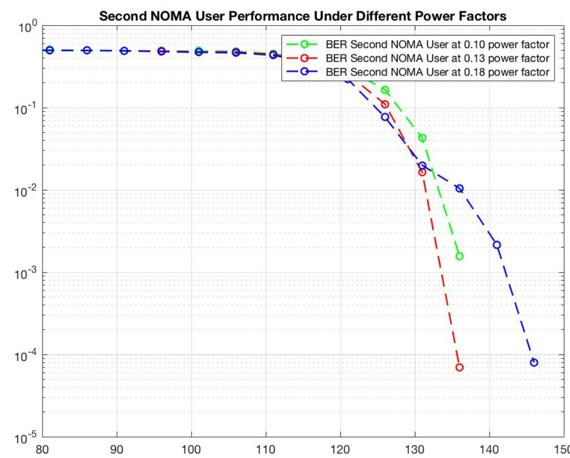

Fig. 7. Second NOMA User With Different ρ

the corresponding residual interference of other users is rather insignificant and so is treated as noise [8].

III. NUMERICAL RESULTS

This section analyzes the achievable BER performance of a SSK-NOMA based VLC downlink scenario for the considered set up and channel conditions. Without the loss of generality, we consider an indoor room with dimensions of 4m $\times$ 4m $\times$ 3m with 4 transmitting LEDs placed at (2.2, 2.2, 3), (1.8, 2.2, 3), (1.8, 1.8, 3) and (2.2, 1.8, 3). Moreover, we assume one SSK user and two NOMA users in the area covered by the transmission range of the LED. It is noteworthy that the number of users mentioned in the analyzed scenario is solely indicative. As already mentioned, the considered system is general and can be applied for any number of users. From this perspective, the LED superimpose a NOMA signal for two users with allocated power values to each user respectively, spatially to SSK user as the same time. Where one LED is actively transmitting the signal at an instant, encoding its index to SSK user and the superimposed NOMA signal. The system parameters values are depicted in Table I.

The corresponding performance is evaluated with respect to the SNR transmitted from transmitting LEDs, for the purpose of taking into account the path gain of each individual user. The corresponding BER performance of SSK user is shown in Figure 6. It is noted here that the BER performance of NOMA users is analyzed for different values of ρ (between 0 and 1), with the best performance achieved for ρ = 0.1 as seen in Figure 6. In the same context, Figs. 6 and Fig 7 demonstrate the corresponding BER performance as a function of ρ. Evidently, the best performance is observed that the best performance for NOMA is when ρ either 0.1 - 0.13. Finally, the the performance of NOMA was analyzed in [8], where it showed an optimal performance for certain values of ρ.

IV. CONCLUSION

This work inverstigated the BER performance in a downlink VLC network in the context of NOMA with SSK modulation. It was shown that SSK modulation in VLC exhibits adequate performance and a moderate system complexity. Furthermore, the offered results quantified the effect of different ρ values on the overall system performance and insights were developed. It was also shown that the low complexity and high performance of the considered hybrid renders it a suitable option for effective communication scenarios in the context of emerging wireless technologies.

Acknowledgment

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