Optical Non-Orthogonal Multiple Access for Visible Light Communication

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Optical Non-Orthogonal Multiple Access for Visible Light Communication

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Abstract—**The proliferation of mobile Internet and connected devices, offering a variety of services at different levels of performance, represents a major challenge for the fifth generation wireless networks and beyond. This requires a paradigm shift towards the development of key enabling techniques for the next generation wireless networks. In this respect, visible light communication (VLC) has recently emerged as a new communication paradigm that is capable of providing ubiquitous connectivity by complementing radio frequency communications. One of the main challenges of VLC systems, however, is the low modulation bandwidth of the light-emitting-diodes, which is in the megahertz range. This article presents a promising technology, referred to as "optical- non-orthogonal multiple access (O-NOMA)", which is envisioned to address the key challenges in the next generation of wireless networks. We provide a detailed overview and analysis of the state-of-the-art integration of O-NOMA in VLC networks. Furthermore, we provide insights on the potential opportunities and challenges as well as some open research problems that are envisioned to pave the way for the future design and implementation of O-NOMA in VLC systems.**

INTRODUCTION

The explosive growth of connected devices, due to the emergence of Internet of Things (IoT) and the growing number of broadband mobile subscribers, which is expected to be around 8.6 billion subscribers by 2020 [1], will lead to an unprecedented growth in traffic demand. In this respect, the next generation wireless networks are envisioned to meet this growth and offer a projected data rate of 20 Gbps, posing new technical challenges to address the requirement for low latency and high spectrum efficiency. The ongoing research efforts have mainly focused on two main directions: 1) enhancing the spectral efficiency of the available radio frequency (RF) spectrum by adopting advanced modulation schemes, new multiple access techniques and efficient bandwidth reuse; and 2) exploring the potentials of the unlicensed spectrum, i.e., Infrared (300 GHz - 430 THz) and visible light spectrum (430 THz - 790 THz). In this context, visible light communication (VLC) has emerged as a promising small cell technology that can be connected to the existing super fast fiber networks and constitutes an integral part of the future ubiquitous fifth generation (5G) communication systems.

A VLC system uses off-the-shelf standard light-emitting diodes (LEDs) to enable high speed data transmission and, simultaneously, to provide indoor/outdoor illumination. It can be realized by modulating and demodulating the light intensity of the LEDs in a process known as intensity modulation and direct detection (IM/DD). The most attractive features of VLC are the inherent communication security, the high degrees of spatial reuse, and its invulnerability to RF interference, which renders it safe for operation in environments with high electromagnetic interference (EMI), such as hospitals and industrial plants. Furthermore, visible light cannot penetrate through most objects and walls, making it well-suited for small cell design and capable of providing high quality services without inter-cell interference. This constitutes VLC a viable attractive technology and an effective complement to current RF communications.

Nonetheless, in spite of its great advantages, VLC systems have certain shortcomings which need to be fully addressed in order to exploit the full potentials of this emerging technology. A key limitation of VLC systems is that the achievable data rates are restricted to the limited modulation bandwidth of the LEDs, which spans few MHz. Therefore, in order to realize the envisioned VLC systems with full potentials, there has been increased interest in the efficient development of advanced optical modulation techniques, optical multiple-input-multiple-output (MIMO) and multiple access schemes.

As a technology enabler for 5G networks and beyond, VLC is envisioned to provide ubiquitous connectivity and high spectral efficiency. To this end, various optical (orthogonal and non-orthogonal) multiple access schemes have been proposed in the open literature, addressing these challenges. In orthogonal multiple access (OMA), different users are allocated to orthogonal resources in either the frequency or time domain. For example, orthogonal frequency division multiple access (OFDMA) assigns different frequency sub-carriers to different users, whereas time division multiple access (TDMA) allows users to share the same frequency by accessing the network in a rapid succession during their assigned time slots.

On the contrary, non-orthogonal multiple access (NOMA) allows multiple users to simultaneously utilize the entire available frequency and time resources, leading to superior enhancements in spectral efficiency compared to OMA schemes.

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NOMA can be realized via two different approaches, namely, power-domain (PD) NOMA and code-domain (CD) NOMA. In PD NOMA, users are multiplexed in the power domain by assigning distinct power levels to different users, while CD NOMA utilizes user-specific spreading sequences in order to multiplex the users in the code domain similarly to the well known code division multiple access (CDMA) technique.

It is worth noting that PD NOMA has been shown to be particularly suitable for VLC downlink (DL) systems for several reasons [1]. First, PD NOMA is typically used to multiplex a few number of users, which is in-line with the requirements of VLC systems that employ LEDs as small cells to serve a small number of users. Second, power allocation in PD NOMA is exclusively dependent on the channel state information (CSI) available at the transmitter, and channel estimation in VLC is considerably less error-prone, compared to RF, due to the time-invariant channel gain that remains constant until the location of the receiving terminal changes. Third, PD NOMA performs better in high signal-to-noise ratio (SNR) scenarios, which is the case in VLC systems due to the strong line-of-sight (LOS) channel gain and the short separation between the communication front ends. Finally, the performance of PD NOMA systems can be improved by enhancing the channel gain differences between users, which can be achieved by tuning the transmission angles of the LEDs and the field-of-views (FOVs) of the PDs, offering two degrees of freedom to optimize the system performance. *Henceforth, we refer to PD NOMA in VLC, which is the focus of this article, as optical (O)-NOMA.*

Basic Concepts of O-NOMA

O-NOMA allows different users to share the same time and frequency resources in the power domain, leading to enhanced capacity gains. Fig. 1 illustrates the main components of a two user O-NOMA with a successive interference cancellation (SIC) receiver. In O-NOMA, power-domain multiplexing is performed by assigning different power values to the signals of the different users and transmitting them simultaneously. This process is referred to as superposition coding (SC) while multi-user detection is realized using SIC at the receiving terminals. In the following subsections, we provide an overview of the basic concepts of O-NOMA.

Superposition Coding

The concept of SC was first introduced in [2], where a transmitter can simultaneously convey different information signals to several receivers in a downlink broadcast channel. In O-NOMA, SC is realized by allocating high power values to users with unfavorable channel conditions and vice versa. In Fig. 1, the LED transmits the unipolar real signals x_1 and x_2 to U_1 and U_2, respectively. Since U_2 is closer to the transmitting LED and thus, has a higher channel gain, the access point assigns a lower power level to x_2. The two signals are then superimposed and transmitted simultaneously as $s = P_1x_1 + P_2x_2$, where $P_1 > P_2$ and the sum of the assigned power values is equal to the total LED transmitting power. The same principle applies for higher number of users,

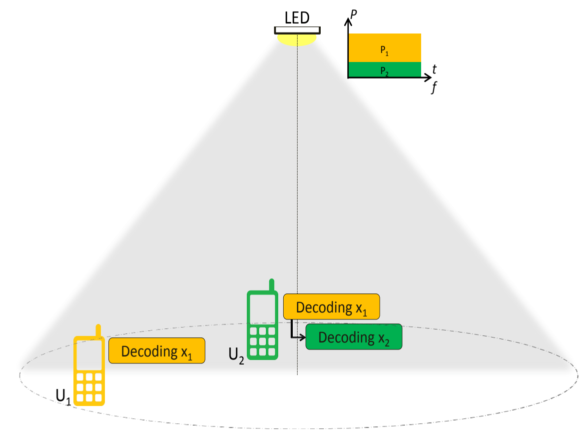


Fig. 1: Downlink NOMA VLC with two users.

where the allocated power values are determined based on the channel gains of the different users.

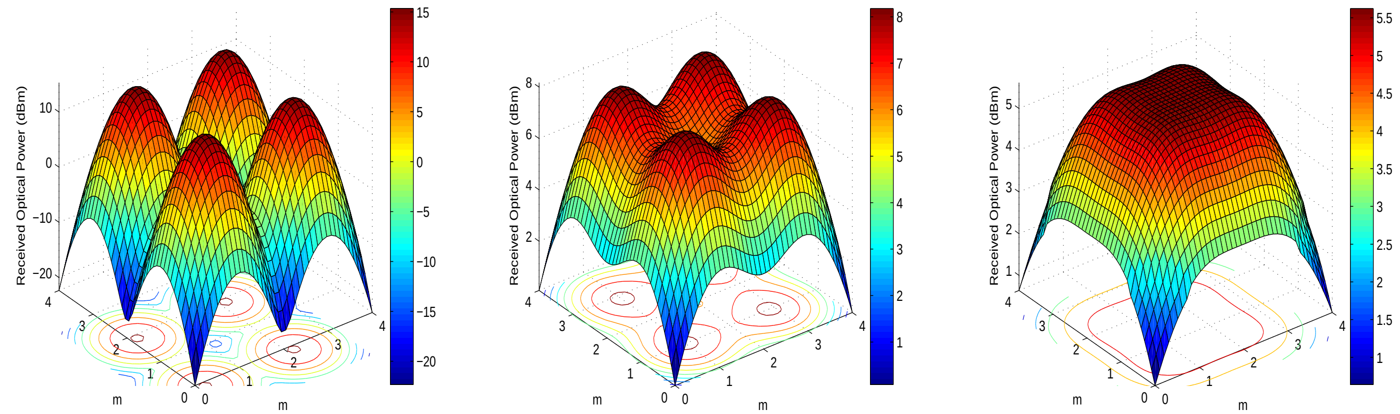
Successive Interference Cancellation (SIC)

Since the dominant component in the combined received signal in Fig. 1 is P_1x_1, U_1 can directly decode its signal by treating the interference from the other user's signal as noise. However, U_2 must decode x_1 first, and then subtract it from the combined signal in order to isolate x_2 from the residue. This process is called SIC where the involved users are ordered according to their respective signal strengths, so that each receiving terminal decodes the strongest signal first, subtracts it, and repeats the process until it decodes its desired signal.

Power Allocation in O-NOMA

O-NOMA allocates more power to users with worse channel conditions, while less power is allocated to those with better channel conditions. A key element in this approach is to allocate appropriate power levels for the different users in order to facilitate SIC and to achieve better trade-off between throughput and fairness. The simplest power allocation strategy is the so-called fixed power allocation (FPA) [3], in which users are sorted in an ascending order according to channel gain values. The power assigned to the i^{th} sorted user is calculated as $P_i = \alpha P_{i-1}$, where $0 < \alpha < 1$. It is noted that FPA does not require the exact channel gain values of the users, but rather their respective ordering which mainly depends on the users' distances from the transmitting LED.

In [1], a gain ratio power allocation (GRPA) strategy was proposed, where the power assigned to the i^{th} sorted user is given by $P_i = (h_1/h_i)^i P_{i-1}$. Since GRPA takes into account the actual channel path gains of all users, it was shown to provide better performance compared to FPA. The performance of O-NOMA systems can be further enhanced by



(a) (b) (c)

Fig. 2: Optical Power Distribution for four transmitting LEDs with (a) $\varphi_{1/2} = 10°$, (b) $\varphi_{1/2} = 25°$ and (c) $\varphi_{1/2} = 45°$.

optimizing the power values according to the users' specific channel conditions. Exhaustive search was conducted in [4] in order to determine the optimum set of power coefficients that maximized the coverage probability of O-NOMA systems. Similarly, an optimal power allocation algorithm was proposed in [5], where the allocated power coefficients were optimized in order to maximize the sum throughput of the multi-user VLC system. The proposed algorithm was shown to outperform FPA and GRPA in terms of the achievable system sum rate. A similar approach was adopted in [6] where the assigned power coefficients were dynamically optimized under quality of service (QoS) constraints to maximize sum rate or max-min rate.

Multi-Cell O-NOMA Networks

To support the explosive growth of mobile data, future wireless networks will continue to evolve, becoming smaller in size and eventually ultra dense to offload and localize traffic and increase the system spectral efficiency. In the next decade, it is expected that ultra dense networks, with small cells, will cover most of indoor and outdoor spaces, providing data rate of 100 Mbps to cell edge users [7]. However, this will result in an increase in frequency reuse and will introduce intolerable interference, limiting the spectral efficiency of the system. In this respect, VLC is envisioned to play a vital role in addressing these challenges, owing to its unique characteristics.

A typical indoor environment usually comprises multiple adjacent LEDs which form bordering or overlapping VLC cells. The VLC cell size is determined by the transmitting angle of the LED and the vertical distance between the LEDs' plane and the plane of the receiving terminals. Fig. 2 shows the optical power distribution in a $4 \times 4 \times 3$ m^3 room with four transmitting LEDs aligned quadratically in a 2×2 array separated by 1 m and centered in the middle of the room, for different values of LED transmitting angle, φ . As shown in Fig. 2, small transmitting angles form narrow beams with clear crisp borders, whereas larger transmitting angles diffuse the transmitted power leading to seamless coverage area. The use of large transmitting angles is useful in broadcast transmissions, e.g. when all users are receiving the same information in a museum or in an exhibition. However, for scenarios with unicast transmissions, the overlapping of the VLC cells causes inter-cell interference, which raises the need for sophisticated interference cancellation techniques.

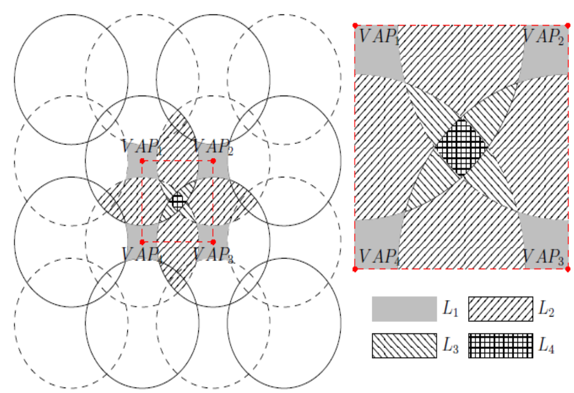


Fig. 3: Multi-cell NOMA VLC network [6]

Inter-Cell Interference

Location-based user grouping was adopted in [6] to mitigate the inter-cell interference in a multi-cell O-NOMA network. The coverage areas were classified into different types according to the degree of the cell overlapping, as illustrated in Fig. 3, where VAP stands for VLC access point. Frequency reuse factor of two was implemented to balance the trade-off between interference cancellation and spectral efficiency, where the bandwidth was divided among two groups of LEDs (represented by solid and dashed lines). Also, user grouping was realized as follows: users in area type L_1 received from a single LED without interference. Users in L_2 received from two overlapping LEDs; however, each LED used a different part of the spectrum, so no interference existed. Moreover, users in area type L_3 could receive from two different LEDs operating in the same bandwidth, so they were scheduled for load balancing. For users in area type L_4, a dedicated part of the bandwidth was reserved since these zones exhibited interference from four different LEDs.

The problem of overlapping VLC cells was further investigated in [8], where a user located in the coverage area of two adjacent LEDs received two signals superimposed in the power domain with different power intensities, depending on the observed channel gains. The user then performed SIC to detect the individual signals from the composite constellation. It was shown that the system performance can be enhanced by applying phase pre-distortion to the transmitted signals to achieve the optimal phase difference between the two channel gains.

A cell zooming approach was proposed in [1] to avoid cell overlapping, which was performed by adjusting the transmitting angles of the LEDs so as to control the respective cell sizes. In the proposed framework, each LED had two different transmission angle settings. A central control unit collected the necessary information about users' locations to configure the transmitting angles accordingly. It is noted here that it is not always feasible to shrink the coverage areas of the LEDs as this may lead to grey holes, i.e., areas with no coverage. Moreover, the adjustment of the transmitting angles may affect the width and intensity of the light beams leading to undesired illumination inconsistency across the indoor space.

Users Association and Handover

In order to ensure seamless user experience in multi-cell NOMA configurations, a location-based users association strategy was proposed in [1]. In particular, a user located in an overlapping area of two adjacent cells was instructed to remain connected to both LEDs, further enhancing the performance of cell edge users. Moreover, the FOVs of the receiving PDs were exploited to reduce the number of handovers. To this end, cell-edge mobile users used wider FOV settings in order to remain connected to their respective home cells for longer periods, avoiding unnecessary handovers. It is worth noting here that a large FOV setting lowers the channel gains at the receiving terminal and, thus, the respective received SNR is reduced.

Hybrid OFDMA/TDMA-O-NOMA

The capacity gain of O-NOMA is achieved by multiplexing different users in power domain while sharing same frequency and time resources. Due to interference constraints, it is impractical to multiplex a large group of users, which is consistent with the nature of VLC systems. This indeed stems from the fact that an LED is regarded as a small cell with a limited number of users existing within a small coverage area. Recent results have demonstrated the multiplexing of up to 5 users using a single LED transmitter. We point out that for larger numbers of users, particularly, in a small cell size, the channel conditions may not differ significantly among users. In this case, OMA can be a better choice and, therefore, hybrid OMA and NOMA can coexist to fulfill a better trade-off between capacity and reliability. To this end, users can be divided into different groups that are multiplexed via OMA technique such as OFDMA or TDMA, whereas the users within each group are multiplexed in the power domain via O-NOMA.

It is evident that the performance of such hybrid schemes is highly affected by the user selection strategy. The impact of users pairing in a hybrid multiple access VLC downlink network was investigated in [9], where users were divided into groups of two and a channel gain-based pairing strategy was adopted. It was shown that the achieved system throughput can be maximized by pairing the two users with the most distinctive channel conditions. It is then clear that the choice of users pairing is not a straightforward problem as we cannot simply pair the users with the most dissimilar channels, leaving users with correlated channels to suffer interference-limited performance. Therefore, optimum user-pairing in hybrid multiple access systems requires sophisticated algorithms to obtain the maximum benefits offered by O-NOMA. Furthermore, although indoor VLC systems typically exhibit low mobility velocity, any small change in the users' locations would change the corresponding channel gain, due to the short distance and the nature of the VLC channel. As a result, low complexity dynamic users-pairing algorithms are required for practical system implementations.

Performance of O-NOMA

The latest research efforts on the performance evaluation of O-NOMA have mainly focused on the capacity gains of O-NOMA, compared to its OMA counterparts. However, the capacity gain naturally comes at the expense of reduced link reliability. It is evident that splitting the power between users leads to a lower received SNR and, consequently, higher error probability. Moreover, the inherit interference implied by power-domain superposition and the cancellation errors that may occur during SIC lead to lower detection accuracy. In this section, we provide an overview of the performance measures of O-NOMA systems, and we develop useful insights into the inevitable tradeoff between capacity and reliability.

System Capacity

The work in [4] and [9] provided analytical and numerical evaluation of the ergodic sum rate for different number of users, where the individual data rates were opportunistically assigned in a best-effort manner based on the users' channel conditions. In the aforementioned study, O-NOMA showed superior performance in terms of the system sum rate compared to OFDMA. Interestingly, it was shown that although the blockage of the LOS channel component degrades the system performance, O-NOMA transmission was still possible due to the existence of multipath reflections. The sum rate performance of a multi-cell O-NOMA network was investigated in [6]. It was shown that employing a frequency reuse factor of two can lead to significant improvement in the achievable sum rate in each cell compared to the case without frequency reuse. Moreover, it was shown that CSI error may lead to degradation in the achieved sum rate of O-NOMA, as it affects the accuracy of the power allocation. Nevertheless, O-NOMA sum rate remained higher than the sum rate of OMA, even with imperfect CSI.

DC-biased optical OFDM (DCO-OFDM) transmissions were considered in [3] for both O-NOMA and OFDMA. It was shown that O-NOMA outperforms OFDMA in terms of the achievable sum rate under zero or low cancellation errors. However, for higher cancellation errors, which may result from inefficient power allocation, the performance of O-NOMA suffered severe performance loss.

Link Reliability

The coverage probability of an O-NOMA system was investigated in [9], where it was defined as the probability that all users in the system achieve a reliable detection. For optimally chosen power coefficients, the system coverage probability was nearly 100% for low target data rate, and it decreased with the increase in the target data rate. Compared to OFDMA, O-NOMA provided higher coverage probability for different target data rates.

The error performance of O-NOMA systems was analyzed in [10] for the case of perfect and imperfect CSI. The derived bit-error-rate (BER) expressions explicitly took channel uncertainty, cancellation errors, and interference terms into account. It was shown that noisy CSI, as expected, leads to a degradation of the system performance. This degradation is rather small compared to the one created by outdated CSI which may result from the mobility of the user between two consecutive CSI updates. In fact, outdated CSI can cause detrimental performance loss if the ordering of the users' channel gains change between the channel updates, leading to unfair power allocation.

Performance Trade-offs

In order to demonstrate the trade-off between capacity and reliability, we simulate the performance of a two-user scenario for both O-NOMA and OFDMA. Fig. 4 and Fig. 5 show the normalized system throughput and the error rate performance, respectively. Both multiple access schemes are based on DCO-OFDM transmission and U_1 indicates the user with a lower channel gain. As can be seen from Fig. 4, O-NOMA provides a significant improvement in the overall system throughput compared to OFDMA. This throughput gain is higher for U_1, since O-NOMA allocates higher power to users with unfavorable channel conditions. However, the observed throughput enhancements provided by O-NOMA come at the expense of performance loss in link reliability, as demonstrated by Fig. 5. As expected, O-NOMA suffers from higher error rate, particularly, for U_2, since it performs signal detection in the presence of interference from the signal of U_1.

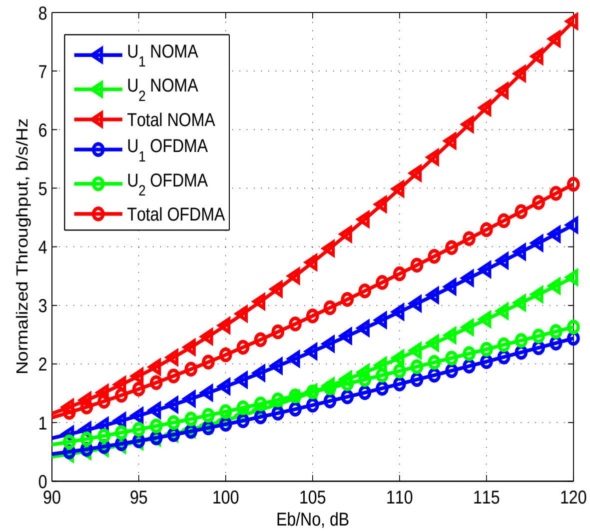


Fig. 4: Normalized System Throughput for Two Users

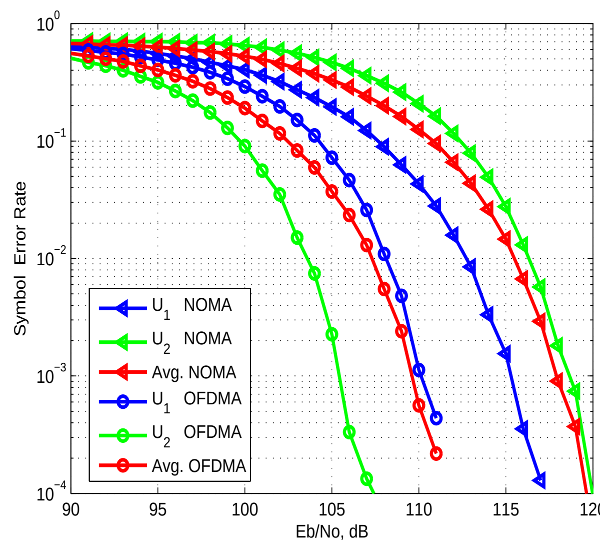


Fig. 5: Error Rate Performance for Two Users

Future Research Directions

So far, we have introduced the ongoing research efforts on implementing O-NOMA. In the following, we identify some interesting research opportunities and challenges related to the practical integration of NOMA in VLC systems.

MIMO-O-NOMA

In order to ensure sufficient illumination, indoor spaces are typically equipped with multiple LEDs. This feature has motivated the implementation of MIMO configurations in VLC systems [11]. MIMO can be used in conjunction with NOMA to provide capacity and reliability improvements. For MIMO with spatial multiplexing (SMP), users can be divided into subgroups where each group receives from a single LED. Within each group, users are superimposed in the power domain; this implies that two levels of interference cancellation are needed: the first level is to separate the MIMO subchannels, which can be attained by means of transmit precoding [12]; the second is the interference cancellation among the multiplexed users of the same LED, which can be performed using SIC. A careful design of the SMP-MIMO NOMA can provide significant capacity enhancement by increasing the number of users that are simultaneously served. On the contrary, MIMO-based repetition coding (RC) can be used to improve link reliability by providing diversity gains. However, the design of such system is not straightforward when O-NOMA is considered. This is because the power allocation should be performed across the aggregate signal depending on the users' channel gains from the different LEDs, which increases the involved complexity specially when users' mobility is considered.

Impact of Channel Symmetry

It has been pointed out earlier that the existence of dissimilar channel gains is the basis of successful detection in O-NOMA. However, the VLC channel implies that the users' channel gains could be particularly close to one another, or even equal, depending on the positions of the receiving terminals. Typical indoor VLC configurations exhibit strong symmetrical channel gains as the LEDs are located in the center of the room, which forms a real challenge in O-NOMA. One possible solution is the adjustment of the transmitters' angles and the receivers' FOVs, as reported in [1]. However, further research is needed to evaluate the performance of O-NOMA in highly symmetrical setups, and to investigate how angles adjustment can be dynamically performed when users' change their locations.

Nonlinear Distortion in O-NOMA

Nonlinear distortions constitute limiting factors of the performance of VLC systems, although they have been overlooked in the majority of recent literature. The most common sources of nonlinearities are the circuits of the LEDs, LEDs, photodiodes, and digital-to-analog/analog-to-digital converters. Furthermore, VLC systems are sensitive to nonlinearities in electrical-to-optical and optical-to-electrical conversion [13]. The impact of nonlinearities on the performance of O-NOMA is not comprehensively understood yet, since it has not been addressed in the related open literature, which demands for a thorough investigation. We note that such an investigation is imperative for the actual realization of O-NOMA and for determining the actual performance limits in terms of both spectral efficiency and error rate performance. Finally, the design of pragmatic compensation strategies to mitigate nonlinear distortions constitutes an important challenge for future high speed VLC systems design, which needs to be addressed before O-NOMA becomes an integral part of future wireless networks.

Other Challenges

Future research and development of O-NOMA in the context of VLC can be directed towards the implementation of O-NOMA in Massive MIMO VLC [14], proper users pairing and power allocation techniques under feedback delay, peak-to-average-power ratio (PAPR) reduction in hybrid OMA-O-NOMA systems, O-NOMA in asynchronous communications, and O-NOMA in uplink VLC.

Conclusions

This article reviewed the emerging concept of power-domain O-NOMA and its integration in VLC systems. A critical review of the state-of-the-art on the design and implementation of O-NOMA VLC allowed us to recognize the underlying performance tradeoffs and the associated research challenges for future work. It was shown that great opportunities exist for the application of O-NOMA in the context of VLC, despite certain restrictions imposed by the nature of VLC channel. We believe that, with a considerate design of O-NOMA, VLC systems can contribute towards meeting the capacity demands expected in future 5G networks and beyond.

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