Multi-user Techniques in Visible Light Communications: A Survey

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***Abstract*—Visible light communication (VLC) is a recent proposed paradigm of optical wireless communication, in which the visible electromagnetic radiation is used for data transmission. The visible part of the spectrum occupies the frequency range from 400 THz to 800 THz, which is $10,000$ times greater than the radio frequency (RF) band. Therefore, its exceptional characteristics render it a promising solution to support and complement traditional RF communication systems, and also overcome the currently witnessed scarcity of radio spectrum resources. To this end, in the last few years, there has been a rapid interest in multi-user processing techniques in VLC. Motivated by this, in this paper, we present a comprehensive and up-to-date survey on the integration of multiple-input multiple-output systems, multi-carrier modulations and multiple access techniques in the context of VLC.**

***Index Terms*—Visible light communication, MIMO systems, multi-carrier, multiple access.**

I. Introduction

Visible light communication (VLC) links can be practically realized by using light emitting diodes (LEDs) as transmitters and photo detectors (PDs) as receivers [1]. In this context, VLC has been gaining increasing popularity in the last few years as a promising solution for highly efficient high daterate wireless access. Based on this, it has attracted a significant interest of academic and industrial sectors [2], [3]. One of the main drivers of this attention is the current scarcity of radio frequency (RF) resources, due to the expanding demand for high-rate wireless communications. Therefore, there is a paramount need to utilize other parts of the available spectrum for data transmissions; in this context, the unlicensed reusable visible band is a potential solution to support and complement RF communications [4]. This can be mainly achieved thanks to the capability of VLC to provide high degrees of spatial reuse, since different transmitting LEDs do not interfere with each other as long as their coverage areas are not overlapping. As a result, VLC offers significantly higher orders of spatial density compared to radio communications while it ultimately exhibits substantially increased security levels [5]. The main reason is that light does not penetrate through walls, and thus, VLC can naturally provide enhanced communication security compared to RF communications, which are susceptible to eavesdropping. It is also recalled that using RF signals can be hazardous in certain environments with high electromagnatic interference (EMI), such as hospitals and industrial plants [6]. Hence, since VLC signals do not interfere with electromagnetic radiations, they are considered safe to be used in such applications [7]. It is also noted that LEDs are undoubtedly the most energy efficient light sources [8], which is the reason why VLC is considered an eco-friendly green technology. To this effect, it is estimated that the global electricity consumption could be reduced to half, if all conventional light sources are substituted by LEDs. Finally, VLC technology can be ultimately integrated into the existing infrastructure with the use of relatively inexpensive baseband components.

However, VLC has also certain shortcomings that are particularly challenging and need to be addressed in order to acquire the inherent benefits of this technological breakthrough in wireless communications. For example, the main drawback of emerging VLC systems is the narrow modulation bandwidth of the light sources. This issue should be effectively resolved to enable the design and deployment of high-rate VLC systems. Motivated by the above, this paper focuses mainly on the recent developments in the field of multi-user VLC systems, with emphasis on VLC in the context of multi-antenna systems, multi-carrier schemes and multiple access schemes. Specifically, the remainder of the paper is organized as follows: Section II summarizes the key contributions in the area of multiple-input-multiple-output (MIMO) configurations in the context of VLC. Section III focuses on multi-carrier VLC systems, while Section IV reviews the multiple access schemes that have been proposed for VLC.

II. MIMO in VLC

MIMO communications have been proposed for VLC systems aiming to overcome the limited modulation bandwidth and provide high data rates. Multiple LED arrays typically exist in indoor environments, which makes MIMO transmissions potentially attractive. Moreover, MIMO configurations can reduce the difficulties in achieving physical alignment between the transmitting LED and the detectors, in scenarios involving users mobility [9]. The simplest MIMO transmission technique is based on repetition coding (RC), in which the same signal is transmitted by multiple LEDs. Although RC can reduce the fading effects in free-space OWC [10], which improves the corresponding system performance, it provides minimal diversity gain in indoor VLC systems. The underlying reason is the high correlation between the line-of-sight (LOS) links from the adjacent LEDs, while the diffuse components are negligible as reported in [11], where it was shown that the strongest diffuse component received is at least 7 dB lower than the weakest LOS component.

Likewise, spatial multiplexing (SMP) is another well-known MIMO concept, which enhances the spectral efficiency of the system by simultaneously transmitting different data signals from multiple LEDs. Moreover, spatial modulation (SM) can be used by incorporating digital modulation in MIMO transmissions [12]. The basic idea in SM is adding an extra dimension (spatial dimension) to the constellation diagram. The spatial dimension chooses a unique transmit antenna for each binary sequence. Thus, an LED is activated only if the symbol to be transmitted matches its pre-allocated spatial symbol, which increases the overall system spectral efficiency by 2^{N_t}, with N_t denoting the number of transmit LEDs.

The performance of the three different MIMO schemes has been evaluated in [13]. It was found that RC is robust to the misalignment between the transmit LEDs and the detectors, yet, it suffers from low spectral efficiency. On the contrary, SMP increases the corresponding spectral efficiency by utilizing multiplexing gains when low correlation exists between the multiple MIMO channels, but the performance gain degrades in the case of the high correlation. Moreover, it was shown that SM can provide spectral efficiency enhancement regardless of high channel correlation, while it has the advantage of lower complexity detection, due to the elimination of inter-channel interference (ICI) [14]. To this end, the work in [15] proposed an optical power allocation scheme in SM-MIMO VLC system based on singular value decomposition (SVD) and adaptive modulation. It was shown that the proposed method outperforms the equal transmit power allocation method in terms of the system's spectral efficiency.

In the case of MIMO systems with SMP, multiple neighboring LEDs simultaneously transmit different information signals resulting in multi-user interference (MUI). Based on this, multiple-input single-output (MISO) precoding schemes have been investigated in [16], to eliminate the inherit interference at each user terminal. Furthermore, a MIMO scenario with block diagonalization precoding was adopted in [17] to eliminate MUI. The previously mentioned investigations assume perfect knowledge of the channel fading coefficients at both the transmitter and the receiver sites. Yet, it is noted that these coefficients must be accurately estimated prior to the design of the precoding matrix. In general, the performance of MIMO precoding techniques depends significantly on the knowledge of the channel-state-information (CSI) at the transmitter site [18]. Recently, the effect of channel uncertainties was considered in [19], where an iterative mean-square error (MSE) minimization problem was formulated to optimize the precoder and equalizer design under both perfect and imperfect CSI.

A precoded multi-user MIMO VLC system was investigated in [20], where SM and spatial pulse position modulation (SPPM) were implemented to enhance the achievable data rate. SM uses the indices of transmitting LEDs to carry additional bits, while SPPM combines both SM and pulse position modulation (PPM). In SPPM, the data stream is divided into two parts; the first part is used to determine the PPM symbol, while the second part indicates the receiver index. Simulation results revealed that while SM-based MIMO configurations achieve high spectral efficiency at high signal-to-noise-ratio (SNR) values, SPPM performs better at low SNR scenarios. The problem of minimizing the maximum power consumption in a multi-user MIMO VLC system was studied in [21], where a linear precoder was designed subject to system capacity and required illumination level constraints. The design of the precoder matrix forms a non-convex optimization problem that is transformed into a convex problem by means of matrix transformation and semi-definite relaxation. Next, the solution is obtained using decomposition theorem. The proposed precoder design was shown to outperform the conventional zero forcing precoding.

An optical adaptive precoding scheme was proposed in [22] to exploit the knowledge of the transmitted symbols to boost the received SNR at the user terminals. The proposed work classified the ICI into constructive and destructive interference, and modifies the precoding matrix so as to only eliminate the undesired interference and keep the constructive interfering symbols. Results showed that the proposed adaptive modulation scheme can provide significant performance enhancement compared to conventional channel inversion precoding.

The impact of multipath reflections was exploited in [23] to improve the achievable throughput of an indoor MIMO VLC system. Throughput gains across different locations of the simulation area were evaluated under RC, SMP and an adaptive SM scheme which determines the transmitters-receivers setup based on the rank of the channel matrix. Performance evaluation was conducted assuming vertical and angular diversity receivers taking into account the LOS propagation as well as two different reflection models, namely Lambertian specular reflections and Lambert Phong diffuse reflections. Results showed that the usage of angular diversity receivers can significantly enhance the received LOS components. Moreover, it was shown that SMP outperforms RC and ASM, and that the reflected optical paths can positively enhance system performance as they constructively contribute to the corresponding LOS component at the receiving terminal.

It is recalled that in RC, SMP and SM based MIMO configurations, the transmitted symbols are independently generated from the constellations. In the context of VLC MIMO systems, a new constellation design, namely collaborative constellation (CC) was proposed in [24]. In CC, the symbols of different transmitters are jointly generated in order to minimize the average transmit optical power for a given minimum Euclidean distance. Simulation results showed that the proposed CC scheme always outperforms SMP and SM in terms of error performance, while it performs better than RC provided that low correlation exists between the channels. Likewise, an optimal constellation for a 2×2 MIMO VLC system was presented in [25], where the available CSI was exploited to select the constellation vectors that maximize the minimum Euclidean distance for a given transmitters-receivers arrangement. The provided results showed bit-error-rate (BER) improvement compared to RC and space shift keying (SSK) modulation.

Finally, receiver designs based on angle diversity were proposed in [26] to achieve MIMO capacity for indoor VLC systems. It was shown that high-rank MIMO channels can be established by employing several PDs with different inclination angles, even if the PDs are closely positioned. Two different designs were presented for the PDs' orientation, namely, pyramid receiver and hemispheric receiver. It was shown that the proposed receiver designs outperform spatially-separated receivers in terms of channel capacity and BER performance, while having the benefit of small size requirements, which renders them applicable in hand-held devices.

III. Multi-Carrier Transmissions in VLC

A. Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) has attracted attention in VLC systems, due to its high spectral efficiency and its robustness to inter-symbol interference (ISI) [27]. Conventional OFDM cannot be directly applied to VLC systems due to the constraints imposed by intensity modulation (IM), i.e., the requirements of real and unipolar valued signal. To satisfy the reality constraint, Hermitian symmetry is applied on the parallel data streams into the IFFT input in OFDM modules. However, this leads to a loss of half of the available bandwidth. Several approaches were presented in the open literature to satisfy the constraint on the positivity of OFDM signals. For example, DC biased optical OFDM (DCO-OFDM) was a proposed solution where a DC bias is added before transmission [28]. This approach requires increasing signal amplitude, which is not desirable in VLC systems as it may lead to signal distortion or cause overheating due to the limited dynamic region of the LEDs. In this context, several peak-to-average power ratio (PAPR) reduction technique were proposed in the technical literature to overcome this limitation [29]–[31]. However, PAPR reduction comes at the expense of increased complexity and BER performance degradation [32]. The work in [33] and [34] proposed optimum DC biasing and scaling factor schemes to reduce the effect of signal distortion caused by clipping.

Asymmetrically clipped optical OFDM (ACO-OFDM) is another optical OFDM scheme where the OFDM signal is clipped at the zero level, to produce a unipolar signal [35]. As a result, only the positive part of the signal is transmitted. This approach is more power efficient compared to DCO-OFDM; nevertheless, the use of only half of the subcarriers for data transmission is inefficient in terms of bandwidth utilization. In the same context, a hybrid ACO-OFDM scheme was proposed in [36], where pulse amplitude modulated discrete multitone (PAM-DMT) modulation is combined with ACO-OFDM, which doubles the system spectral efficiency. However, this scheme may lead to BER performance degradation at low SNR values. A negative ACO-OFDM (NACO-OFDM) scheme was proposed in [37] to enhance the system spectral efficiency. In NACO-OFDM, the ACO-OFDM signal is combined with on-off keying (OOK) modulation such that the positive part of the signal is clipped and transmitted with the OFF part of the OOK signal whereas the negative part is kept and biased by the ON part of the OOK signal. Asymmetrically clipped DC biased optical OFDM (ADO-OFDM) combines the advantages of both ACO-OFDM and DCO-OFDM [38]. In ADO-OFDM, all subcarriers are used to convey data, thus, it is more bandwidth efficient compared to ACO-OFDM. Also, it is more power efficient compared to DCO-OFDM, since ACO-OFDM is applied on half of the subcarriers.

Several improved optical OFDM schemes have been proposed in the open literature to compensate the spectral efficiency loss, such as: Unipolar OFDM (U-OFDM) [39], enhanced unipolar OFDM (eU-OFDM) [40], spectral and energy efficient OFDM (SEE-OFDM) [41] and μ-OFDM [42]. The main idea of these techniques is to combine multiple signals at the transmitter side and demodulate them independently at the receivers.

B. Frequency Division Multiplexing (FDM)

An indoor optical fiber and VLC system that exploits frequency division multiplexing (FDM) was demonstrated in [43]. Experimental results showed that the proposed configuration achieved data rate of 200 Mb/s with acceptable BER performance. The work in [44] presented a VLC-based indoor positioning system (IPS), where the transmitted signals from the LEDs were multiplexed in the frequency domain by means of FDM. Simulation results showed that the FDM-based system outperformed its time division multiplexing (TDM) counterpart in terms of localization error. Moreover, FDM was utilized as an uplink access scheme in a full-duplex VLC local area network as demonstrated in [45].

C. Time Division Multiplexing (TDM)

Time division multiplexing (TDM) was mainly proposed for VLC based IPSs. In such systems, large numbers of LEDs typically exist in the indoor space. Thus, the coverage areas of the LEDs greatly overlap, resulting in high intercell interference (ICI). Consequently, it would be difficult to decide which LED is transmitting a certain signal. TDM was proposed as a potential solution, where each LED is assigned a time slot and transmits signals only in this time slot [44]. In conventional TDM schemes with many transmitting LEDs, it typically takes long to receive another signal from a specific LED. This results to high delay in the LEDs' transmissions, which leads to inaccurate location estimates for a mobile user.

A block encoding TDM scheme was presented in [46] to reduce the system delay. In the proposed scheme, LEDs were divided into groups, and one LED from each group can transmit in a certain time slot, resulting in ICI. In order to overcome ICI, an extended binary coded decimal (BCD) code was implemented to encode the signals transmitted by the

LEDs of the different groups. In [45], TDM was proposed as an uplink access scheme in full-duplex VLC local area network, as it can provide relatively low system complexity compared to FDM. In the proposed scheme, each user has four time slots in which it can transmit, and, the source of each data stream can be recognized based on the time domain schedule.

D. Code Division Multiplexing (CDM)

An IPS was proposed in [47] to allow a receiver to determine its location from the LEDs' signals. This can be realized only if the receiver can successfully separate the incoming signals from the different LEDs. To allow this, the LEDs' signals were multiplexed by means of code division multiplexing (CDM). In the proposed scheme, all transmitted signals share the same frequency band, but each of them is modulated with a unique quasi-orthogonal code to enable decoding at the receiver. The presented system was experimentally validated; however, the implementation of high data-rate CDM-based VLC systems has not been yet verified.

E. Wavelet Packet Division Multiplexing (WPDM)

Wavelet packet division multiplexing (WPDM) is a multicarrier scheme that employs wavelet packet function with finite length in time domain as a basis function. The first WPDM-based VLC system was proposed in [48]. WPDM can be viewed as an efficient alternative to OFDM, due to its high spectral and power efficiency as well as lower peak-to-average power ratio (PAPR). Moreover, WPDM is less sensitive to ISI since inter-symbol orthogonality is obtained by the waveforms shift orthogonal characteristic. Thus, cyclic prefix (CP) is not needed for ISI mitigation.

IV. Multiple Access Schemes in VLC

A. Orthogonal Frequency Division Multiple Access (OFDMA)

Optical orthogonal frequency division multiple access (O-OFDMA) was proposed in [49] as a candidate multiple access scheme for VLC systems. O-OFDMA is an OFDMA scheme tailored to IM by being asymmetrically clipped at zero level after OFDM modulation. In the mentioned paper, O-OFDMA was compared to optical orthogonal frequency division multiplexing interleave division multiple access (O-OFDM-IDMA). O-OFDM-IDMA outperforms O-OFDMA in terms of power efficiency, while O-OFDMA has the advantage of lower decoding complexity. Simulation results showed that O-OFDMA provides better PAPR performance compared to O-OFDM-IDMA for high data rates. In this context, two handover mechanisms for indoor O-OFDMA based VLC network were proposed in [50]. The first handover mechanism is called the power-based soft handover, in which a user that exists in the intersection area of two LEDs receives the same data streams from both LEDs and combines them. The second mechanism is called frequency-based soft handover, in which the transmitting LEDs serve users in the intersection area using a reserved frequency band, which compensates the low signal-to-interference-and-noise ratio (SINR) at the receiver. An O-OFDMA VLC system based on DCO-OFDM was proposed in [51], where effective base stations cooperation strategy was implemented to enhance the spectral efficiency of the downlink network. The cooperation was achieved by means of a relay assisted transmission using non-orthogonal amplify-and-forward protocol. Simulation results showed that the proposed strategy substantially outperforms non-cooperative schemes in terms of the system spectral efficiency.

B. Interleaved Frequency Division Multiple Access (IFDMA)

Interleaved frequency division multiple access (IFDMA) was proposed for downlink VLC networks in [52] to overcome the high PAPR limitation in O-OFDMA. It was shown that IFDMA-based VLC systems are less affected by the non-linear characteristics of the LEDs and thus can offer higher power efficiency. Moreover, IFDMA offers lower computational complexity compared to O-OFDMA as it does not involve discrete Fourier transform or inverse discrete Fourier transform operations. Experimental results showed that IDFMA is a promising multiple access scheme for VLC and that it can lead to further performance enhancements by CP insertion, which ultimately mitigates multi-path distortion and reduces synchronization errors.

C. Code Division Multiple Access (CDMA)

Code division multiple access (CDMA) is a non-orthogonal multiple access scheme that can provide high spectral efficiency compared to orthogonal multiple access schemes such as OFDMA and TDMA. An experimental optical code-division multiple access (OCDMA) VLC system was demonstrated in [53]. This scheme allows simultaneous transmissions from different LEDs using random optical codes as coding sequences. To combat the undesired correlation characteristics in random optical codes, a synchronization mechanism was proposed in [54] to achieve better performance in an OCDMA-based VLC system. In [55], OCDMA-VLC system based on OFDM was proposed. Notably, the proposed scheme combines the robustness of OFDM with the flexibility of OCDMA to exhibit better performance.

A low cost OCDMA-based VLC system was proposed in [56], where the signals from different transmitted LEDs were coordinated to achieve interference-free links while carrying essential information to allow users to decode their signals successfully without any pre-configuration. However, the communication range considered in the paper was less than a meter, which does not give a practical indication for the applicability of the proposed scheme to realistic scenarios. The problem of power allocation in a multiuser indoor VLC network based on OCDMA was investigated in [57]. Two distributed power allocation methods were proposed, namely, a partial jointly optimized power allocation and a weighted distributed power allocation. The presented results showed that the proposed algorithms can provide low computational complexity compared to centralized power allocation while the performance penalty is minimal. An OCDMA-based VLC system that supports multiple access with varying data rates was proposed in [58]. It was shown that the proposed scheme, which employs micro-LED arrays, exhibits higher modulation bandwidth and is able to support higher numbers of users.

D. Non-orthogonal Multiple Access (NOMA)

Non-orthogonal multiple access (NOMA), also known as power domain multiple access, was proposed in [59], [60] as a promising bandwidth-efficient solution for multiple access in indoor VLC networks. NOMA is based on the concept of superimposing users' signals in the power domain, where each signal is allocated a distinct power level based on the channel conditions of users. To this effect, all users can exploit the entire available bandwidth for the whole time, which results in a substantial increase in the achieved spectral efficiency. The basic principle of NOMA is that it assigns more power to users with non-favourable channels compared to those with favourable channels. To this effect, the user with the highest power can detect the corresponding information signal, despite the incurred interference from other users, while the other involved users perform successive interference cancellation (SIC) to decode their respective signals. Importantly, it was shown in [61] that NOMA outperforms OFDMA in terms of the achievable data rate in a VLC system. Similarly, the performance of indoor NOMA VLC systems was investigated in [62] where it was shown that NOMA scheme can significantly improve the corresponding system capacity.

V. Conclusion

VLC technology has emerged as a promising future broadband technology to support conventional RF communications. The main limitation in VLC systems is the limited dynamic range of the LEDs which limits the transmission bandwidth. Consequently, enhancing the achievable data rates in VLC systems has been an active research area. To this end, different multi-user and multi-carrier techniques have been adapted to be used in the context of VLC. In this paper, we have provided an up-to-date comprehensive survey on MIMO, multi-carrier and multiple access schemes that have been proposed in the open technical literature and have demonstrated great advances in the achievable data rates in VLC systems.

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