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Spatial and Wavelength Division Multiplexing for High-Speed VLC Systems: An Overview

(Invited)
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Abstract—White light emitting diodes (LEDs) are becoming the primary source of illumination for the home and office environment. These LEDs can be intensity modulated to transmit high-speed data via an optical carrier. As a result, there is a paradigm shift in indoor wireless communication as the illumination infrastructure can be reused for data communications. It is widely expected that visible light communication (VLC) system will play a significant role in realizing the high-speed data communication envisaged for 5G connectivity. The goal of VLC systems is to provide a reliable and ubiquitous communication link that is an order of magnitude faster than current radio frequency (RF) links. In order to support the high data rates required for the current and future generations of communication systems, a number of techniques were explored for VLC by a number of research groups worldwide. This paper provides an overview of spatial and wavelength division multiplexing that has enabled multi-Gb/s transmission speeds in VLC using low bandwidth LEDs.

Index Terms—Visible light communication, spatial multiplexing, MIMO, wavelength division multiplexing

I. INTRODUCTION

THE exponential growth in mobile and internet traffic has already exhausted the available radio frequency (RF) spectrum. The growth in connectivity requirements for end-users are not slowing down and it is predicted that internet traffic will double every two years [1]. The fifth generation (5G) network, with standardization by 2020, is expected to meet these demands by supporting Gigabit/s end user in the home and office environments. In order to achieve Gigabit/s data rate, millimeter wave in the range of 3-60 GHz is proposed, which operates in a line of sight (LOS) similar to optical wavelength. Hence, it is widely expected that visible light communication (VLC) systems will play a key part of 5G connectivity especially for indoor environment [2].

VLC uses the visible range of the electromagnetic spectrum from 370 to 780 nm as the carrier. These wavelengths have a number of advantages over using the RF spectrum. The visible spectrum is unregulated and does not require a license to operate. Due to high directionality, VLC can support dense spatial multiplexing. VLC, on the other hand, also have a

number of shortcomings, mostly due to the way light is modulated. Due to the use of intensity modulation and direct detection (IM/DD), VLC does not offer the same receiver sensitivity as that of an RF receiver. VLC system is susceptible to shadowing and blocking. Nonetheless, it is expected that VLC and RF communication complement each other and co-exist in the future access network communication ecosystem.

Interest in VLC systems grew rapidly over the last decades. Earlier demonstrations of VLC used commercial phosphor based white LEDs [3], [4]. Due to the long photoluminescence lifetime of the yellow phosphor, the white light bandwidth is limited to a few MHz. The bandwidth of the blue spectrum from the LED itself is in the range of 10's MHz. Hence, initial VLC system demonstrations predominately used only high bandwidth blue spectrum by filtering out the slow yellow components at the receiver. Besides optical filtering, a number of advanced and computationally complex techniques had been devised to overcome the bandwidth limitation. As a result, the achievable data rate grew from a humble 100's of Mb/s in 2007 [3], [4] to 10's of Gb/s in 2016 [5]–[7]. In order to make the Gb/s data rate feasible with a low bandwidth system, a number of advanced and computationally complex technologies have been adopted. In this paper, an overview of two key technologies namely, spatial multiplexing and wavelength division multiplexing (WDM) is presented. The rest of the paper is organized as follows: Section II describes the fundamental of spatial multiplexing and modulation. A number of approaches used for a multi-LED system to achieve high data rates are described along with the optical systems and decoding algorithms. Section III is focused on the WDM for VLC. Finally, the current status and future outlook are detailed in Section IV.

II. SPATIAL MULTIPLEXING/MODULATION

In order to meet the illumination requirements, a large number of LEDs are deployed within a confined area. These LEDs can be spatially separated or in a close proximity. With the chip-on-a-board (CoB) concept, a large number of LEDs can be fitted within a single light bulb. VLC systems can take advantage of the availability of multi-element, multi-colored illumination devices to improve coverage, data rate and reliability of the communication system by exploiting spatial separation and WDM.

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There are two approaches to drive multiple LEDs with the incoming data stream:

- a) ganging approach
- b) multiple-input-multiple-output (MIMO) approach

A. Ganging Approach

In the ganging approach, individual LEDs carry identical information, i.e. they are modulated with the same data streams, as shown in Fig. 1(a). Each LED can have an individual driver or can be connected in series or parallel and driven by a single driver. In [8], Le Minh *et al* used 16 transmitters and a single receiver to improve the signal-to-noise ratio (SNR) and demonstrated a 40 Mb/s VLC link using on-off Keying non-return-to-zero (OOK-NRZ) modulation scheme. A ganging scheme with transmitter angle diversity can provide wider coverage. In the angle diversity schemes, limited divergence angle transmitters are pointed in different directions to serve a specific coverage area [9]. Angle diversity can be achieved by a planar array of LEDs in combination with optics as in [10] or by arranging LEDs in a semi-spherical base with each LED pointing in different directions [9], [11]. Similarly, the receiver diversity can provide a larger field of view (FOV), improved SNR and immunity against blocking [12], [13]. In [12], a spatial diversity receiver with maximum ratio combining was considered for a single input multiple output system, thus enhancing the bit error rate performance. The coverage and mobility of a VLC system were both improved by applying a selection combining in conjunction with angle diversity receiver [13].

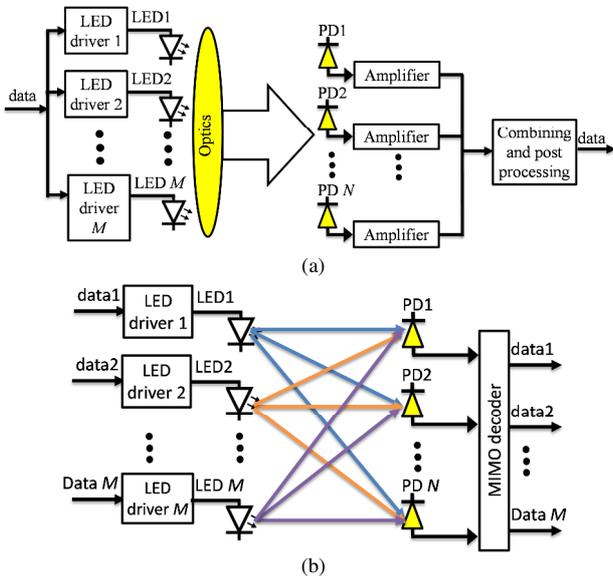


Fig. 1: Approaches to drive multiple LEDs using individual driver a) ganged approach and b) MIMO approach

B. MIMO approach

In the ganging approach, the SNR increases linearly with the number of transmitters. However, based on Shannon's theorem, the system capacity increases logarithmically with SNR. The MIMO scheme, on the other hand, has the potential

to linearly increase the capacity with the minimum number of transmitters by transmitting a parallel stream of data over a common channel. A simplified schematic of a MIMO scheme for VLC is shown in Fig. 1(b) with M transmitters and N receivers. The MIMO system can be modeled as:

$$\mathbf{y}(k) = \mathbf{H}\mathbf{x}(k) + \mathbf{n}(k) \quad (1)$$

where $\mathbf{x}(k)$ is an $(M \times 1)$ transmitted signal vector, $\mathbf{y}(k)$ is an $(N \times 1)$ received signal vector, $\mathbf{n}(k)$ is an $(N \times 1)$ noise vector and \mathbf{H} is an $(N \times M)$ channel matrix. For optimal MIMO operation, the channel \mathbf{H} -matrix must be of full-rank. For the channel \mathbf{H} -matrix to be full-rank in IM/DD system, the number of receiver should be equal to or larger than number of transmitter i.e. $N \geq M$ [8].

There are a number of MIMO techniques for VLC systems. The unique features and advantages these techniques are reviewed in the following section.

1) Spatially superposed modulation

In the spatially superposed modulation scheme, weighted optical intensities from LEDs are superposed in free space to achieve a desired signaling scheme at the receiver plane. One of the simplest schemes is the superposed pulse amplitude modulation (SPAM). In SPAM, weighted OOK-NRZ signals of different optical amplitude are overlaid in free space/fiber as outlined in [14]–[17]. The required weights can be obtained by clustering a different number of LEDs together and driving them with equal intensity [17] or by independently adjusting the modulation current of individual LEDs [14]. A key advantage of this technique is that multi-level PAM is enabled by simple on-off modulation; hence, the effect of LED nonlinearity is significantly reduced.

The spatial superposition scheme is also used for orthogonal frequency division multiplexing (OFDM) to reduce the peak-to-average power ratio (PAPR). In [18], [19], an OFDM signal was divided into a number of narrowband OFDM signals which have a lower PAPR than the OFDM symbol. These signals are then transmitted simultaneously using different LEDs. It is shown that a spatial optical OFDM outperforms other variation of OFDM schemes.

2) Space shift keying

Space shift keying (SSK), also known as optical spatial modulation (OSM), encodes data within the spatial location of LEDs. An example block diagram of SSK with four transmitters is shown in Fig. 2. In SSK, only one LED out of M LEDs is active during one symbol duration. The selection of the LED depends on the incoming data stream. For example, in the illustration in Fig. 2, the LED1 is active for incoming bits of '00', LED2 for '01' and so on. The receiver decodes the data based on the light intensity, which depends on the relative position of the transmitters. Since each LED encodes more than a single bit of information, the SSK improves the spectral efficiency by a factor of $\log_2(M)$ in comparison to OOK-NRZ. By taking advantage of the wavelength dependent responsivity factor of a silicon photodiode (PD), the differentiability of SSK channels can be improved significantly by employing different wavelength LEDs at different locations [20].

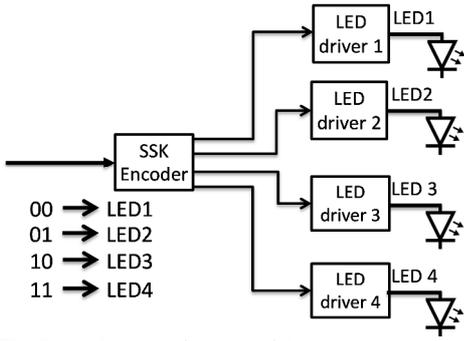


Fig. 2: A schematic of space shift keying

The error performance of SSK depends on the differences in the channel gains of the spatially separated LED array, which limits the receiver mobility [21]. The OSM has also been applied in conjunction with optical OFDM to improve the throughput [22], [23].

3) Spatial multiplexing

In the spatial multiplexing (SMP) scheme, each transmitter carries an independent data stream, thus enhancing the spectral efficiency by up to a factor of M . The data at the receiver is separated by inverting the channel \mathbf{H} -matrix. In order to successfully decode the signal at the receiver, it is necessary that the channel matrix must be full rank and hence the condition $N \geq M$ must be satisfied as previously mentioned [8], [24].

C. Optics for MIMO receiver

Typically, a VLC receiver consists of an imaging/non-imaging concentrator on the top of a photodiode (PD). The optical system offers an optical gain and improves SNR at the receiver albeit at the expense of the reduced FOV. The Conservation of Etendue governs the maximum theoretically achievable optical gain for a given FOV and hence there is a trade-off between the maximum gain and FOV. This section provides an overview of imaging and non-imaging optics for MIMO-VLC system.

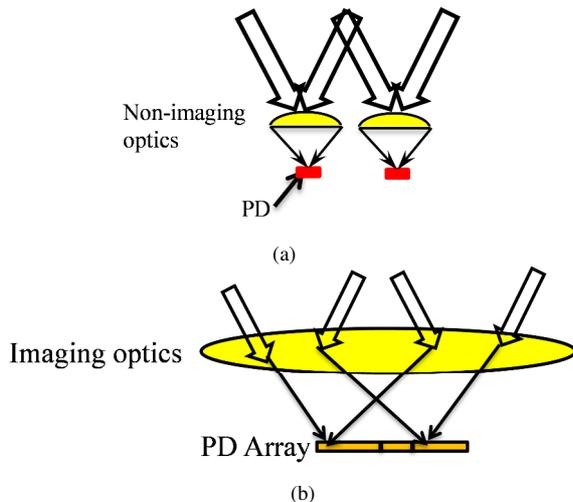


Fig. 3: A schematic of MIMO optics a) non-imaging and b) imaging.

A schematic of non-imaging MIMO receivers is shown in Fig. 3(a). It consists of a number of PDs with the individual optical concentrator. The non-imaging optical MIMO system can theoretically have an ill-conditioned matrix that is not full rank when the transmitter and receiver positions are symmetric. If the \mathbf{H} -matrix is not a full rank, it will be non-invertible and cause a high bit error rate [8]. However, a non-invertible matrix is rarely witnessed in a practical system [25], [26].

Imaging receivers form an image of the transmitter elements onto the receiver array as shown in Fig. 3(b). For an imaging system to successfully separate MIMO channels, the image of more than one transmitter should not fall entirely on a single receiver [24]. With an appropriate optical system, the MIMO channel can be de-correlated optically, making MIMO decoding simpler. An aspheric lens or combination of lenses can be used to design the imaging optics [27]–[30].

D. MIMO decoding algorithms

The spatial intra-channel interference (ICI) and temporal intersymbol interference (ISI) are similar in nature and hence all the temporal equalization techniques like zero-forcing (ZF), minimum mean-squared error (MMSE) and decision feedback (DF) algorithms can be utilized for decoding MIMO channels.

The simplest method to recover the transmitted signal from a received MIMO signal is by using a linear method like a ZF or MMSE algorithms. In the linear approach, the transmitted signal is estimated from received signal \mathbf{y} by linearly combining the elements of \mathbf{y} with a weight vector, \mathbf{W} i.e. the estimated transmitted signal is given by:

$$\hat{\mathbf{x}}(k) = \mathbf{W}\mathbf{y}(k). \quad (3)$$

In the ZF algorithm, the inference is nullified by multiplying the received signal with the pseudo-inverse of the channel matrix \mathbf{W}_{ZF} as given below:

$$\mathbf{W}_{ZF} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H; \quad (4)$$

where \mathbf{H}^H is the conjugated transpose of \mathbf{H} .

The ZF algorithm, however, enhances the noise and as such results in performance degradation. An alternative MMSE algorithm improves the performance in the presence of noise by minimizing the noise and interference simultaneously. The pseudo inverse \mathbf{W}_{MMSE} of \mathbf{H} using MMSE is given by [31]:

$$\mathbf{W}_{MMSE} = \left(\mathbf{H}^H\mathbf{H} + \frac{1}{SNR}\mathbf{I} \right)^{-1} \mathbf{H}^H; \quad (5)$$

where \mathbf{I} is a $M \times M$ identity matrix.

A non-linear approach like vertical Bell Labs layered space-time algorithm (V-BLAST) performs better than the linear approach. The V-BLAST algorithm employs an estimation and successive interference cancellation strategy i.e. the strongest signal is estimated first, and then the inference from this symbol is removed from remaining symbol. Then the next strongest symbol is estimated followed by inference removal. The V-BLAST algorithm is equivalent to a DF equalizer [32].

The optimum decoding strategy is the maximum likelihood (ML) detection i.e. a symbol is selected from all possible combinations that has the smallest difference with the received signal i.e. it finds \mathbf{x} with

$$\arg \min \|\mathbf{y}(k) - \mathbf{H}\mathbf{x}(k)\|. \quad (6)$$

ML offers the best performance. However, the computational complexity increases exponentially with the number of parallel channels or constellation levels.

E. Performance comparison and recent demonstrations

Among the spatial diversity schemes discussed here, the spectral efficiency improves in the order of ganging, SSK, and SMP; as with the receiver complexity. The ganging approach does not provide any MIMO gain in a true sense. In order to improve the spectral efficiencies in the ganging scheme, the constellation size needs to be increased. SMP offers the highest spectral efficiencies. The SMP, however, is computationally complex and its performance also highly dependent upon the channel correlation [33]. The SSK avoid spatial interference by making only one transmitter active at any time. This improves the power efficiency at reduced spectral efficiency. A study in [34] shows that SMP outperforms SSK for higher spectral efficiencies (8 bits/sym) whereas SSK offers improved performance at lower spectral efficiencies (4 bits/sym).

A number of MIMO-VLC system using imaging and non-imaging optics were demonstrated over the last ten years. Wang *et al* demonstrated a 2×2 non-imaging MIMO VLC system with an aggregate data rate of 500 Mb/s [35]. In this study, frequency domain equalization was used to simultaneously de-multiplex and equalize the received signal. They further improved the data rate up to 1.4 Gb/s using an imaging system [36]. Burton *et al* studied a 4×4 non-imaging MIMO system providing a wide coverage range [25]. Each channel combined 4 LEDs driven with an analog pre-equalizer circuit. An error-free data rate of 50 Mb/s was achieved over a distance of 2 m using OOK-NRZ modulation. It was also concluded that ZF offers similar performance to other computationally complex demultiplexing algorithm. Haigh *et al* used ZF de-multiplexing with neural network based equalizer to improve the performance of a 4×4 MIMO organic VLC [37]. The aggregate data rate of 1.8 Mb/s was achieved using white LEDs and four large area organic photodetectors (without any optics).

The study in [8], [34] clearly demonstrated imaging MIMO offers a significant gain over non-imaging MIMO for a VLC system. Imaging MIMO has been adopted mostly for high data rate applications and also to make receiver structure compact. Using four transmitters and nine receivers, Azhar *et al* demonstrated Gb/s transmission imaging MIMO system which is robust to vertical and horizontal displacements within the coverage area [28]. Using high bandwidth micro-LEDs, a higher data rate of 1.5 Gb/s were demonstrated [38]. With a Fisheye-lens-based imaging receiver, an aggregate data rate of 1.3 Gbit/s was demonstrated using four transmitters [39]. An integrated MIMO VLC system, with custom designed CMOS based LED driver and APD receiver, was demonstrated in [29]. The system used closely spaced planar micro-LED array

and planar APD array and hence was scalable to larger MIMO array. The transmitter and receiver optics were designed in such a way that there was a minimum cross-talk in the perfectly aligned condition. By using joint spatial and temporal equalization for the 4-PAM scheme, a minimum data rate of 1.3 Gb/s was achieved using four channels within the FOV of 3.5 degrees [40]. Further improvement up to 7 Gb/s was achieved using nine channels at the reduced FOV.

III. WAVELENGTH DIVISION MULTIPLEXING (WDM)

WDM allows multiplexing multiple optical wavelength carriers that carry an independent data stream and hence increasing the overall channel capacity. For VLC applications, a white light suitable for illumination can be generated by mixing different amounts of narrowband emission from different sources. By concurrently transmitting information over these wavelengths, the system capacity theoretically increases with the number of wavelengths used. LED emission tends to have a larger full width at half maximum (FWHM) than that of a laser emission. Hence, dense WDM (DWDM) is difficult to achieve using LED sources. Using a WDM-based laser, 100's of Gb/s VLC is feasible [41].

The demonstration of VLC system WDM tends to limit the number of the colors to four (RGB, RGYB) due to commercial availability of only these LED luminaries. In [42], a novel WDM approach using polymer based colour-converters and GaN micro-LEDs was demonstrated. As the emission of polymer based colour-converter can be tuned to different colours, it is feasible to increase the number of WDM channels significantly.

In the WDM VLC system, multiple LEDs with different emission wavelengths are driven independently. The light intensity at different wavelengths is superposed in free space (see Fig. 4(a)) or using a holographic diffuser for a uniform illumination. At the receiver, optical bandpass filters with central wavelength matching the transmitter emission are used to separate WDM channels. A simple WDM receiver design based on optical filters is shown in Fig. 4(b). This approach is adopted in a number of WDM demonstrations [6], [7].

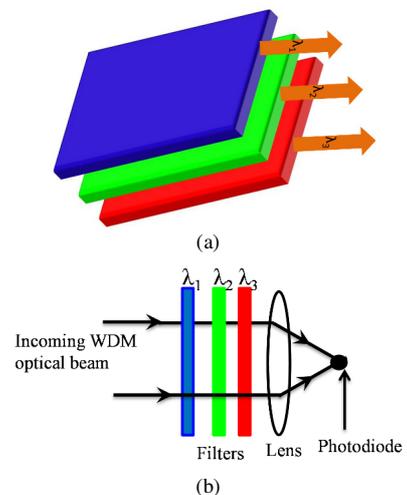


Fig. 4: Schematic of WDM-based VLC system a) transmitter and b) optical filter base receiver

The earliest adaptation of WDM-VLC was reported in [43]. The authors have achieved an aggregate data rate of 803 Mbits/s using a RGB LED and discrete multitone (DMT) with bit and power loading of the quadrature-amplitude-modulation (QAM) constellation. With bit and power loading DMT, Cossu *et al* demonstrated a data rate of 3.4 Gb/s using RGB LEDs and 5.6 Gb/s using a red–blue–green–yellow (RGBY) LEDs [44]. With a non-linear LED response compensation using a Volterra based equalizer, Wang *et al* demonstrated 4.5 Gb/s system using an RGB LEDs [45] and 8 Gb/s using an RGBY LEDs [6]. Chun *et al* studied the impact of the different color combination on the communication system and theoretically established an achievable data rate for different RGB color combinations [5]. A > 10 Gbits/s WDM VLC system was demonstrated by using the simultaneous reception of the entire channels. Using narrowband high bandwidth laser, a higher data rate WDM-VLC is feasible [41], [46].

IV. CURRENT STATUS AND FUTURE OUTLOOK

VLC systems have evolved significantly since its first introduction in the late 20th century. The early demonstrations focused on achieving 100's of Mb/s using a single LED. In less than a decade, a 3 Gb/s rate was demonstrated using a single LED and higher data rate using a laser diode [47]–[49]. With the development of high bandwidth LEDs like micro-LEDs [50], and a wide FOV large gain optical system [51], it is expected that a highly reliable, high data rates length will be feasible at a longer link.

Early demonstrations of VLC used single LEDs with analog equalization and baseband modulation schemes. To improve data rates, the technology advanced from a single wavelength LED to multi-wavelength LEDs [5], [6], [52]; from baseband modulation to carrier based modulation [53]–[55]; from analogue pre and post equalisation to discrete time equalisation [45], [56]; from low bandwidth white LEDs to high bandwidth micro-LEDs [29] or lasers [46], [48]; and from multilevel modulation to spatial multiplexing [29], [57]. As a result, the data rate improved by an order of magnitude within a decade and VLC system is now capable of delivering a data service that exceeds the end-users' current needs. Having witnessed such a rapid growth in research and commercial interest, it is no doubt that the VLC will be a significant part of the future wireless communication system complementing other access technologies.

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REFERENCES

- [1] "Cisco Visual Networking Index: Forecast and Methodology, 2014-2019," 2016.
- [2] C. X. Wang, F. Haider, X. Gao, X. H. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, 2014.
- [3] H. Le Minh, D. O'Brien, G. Faulkner, Z. Lubin, L. Kyungwoo, J. Daekwang, O. Yunje, and W. Eun Tae, "100-Mb/s NRZ visible light communications using a postequalized white LED," *IEEE Photonics Technol. Lett.*, vol. 21, no. 15, pp. 1063–1065, 2009.
- [4] J. Vucic, C. Kottke, S. Nerretter, K. Habel, a. Buttner, K.-D. D. Langer, and J. W. Walewski, "125 Mbit/s over 5 m wireless distance by use of OOK-Modulated phosphorescent white LEDs," in *Optical Communication, 2009. ECOC '09. 35th European Conference on*, 2009, no. 1, pp. 1–2.
- [5] H. Chun, S. Rajbhandari, G. Faulkner, D. Tsonev, E. Xie, J. J. D. McKendry, E. Gu, M. D. Dawson, D. O'Brien, and H. Haas, "LED based Wavelength Division Multiplexed 10 Gb/s Visible Light Communications," *J. Light. Technol.*, 2016.
- [6] Y. Wang, L. Tao, X. Huang, J. Shi, and N. Chi, "8-Gb/s RGBY LED-Based WDM VLC System Employing High-Order CAP Modulation and Hybrid Post Equalizer," *IEEE Photonics J.*, vol. 7, no. 6, pp. 1–7, 2015.
- [7] G. Cossu, A. Wajahat, R. Corsini, and E. Ciaramella, "5.6 Gbit/s downlink and 1.5 Gbit/s uplink optical wireless transmission at indoor distances (≥ 1.5 m)," in *Optical Communication (ECOC), 2014 European Conference on*, 2014, pp. 1–3.
- [8] H. Le Minh, D. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. J. Oh, "High-speed visible light communications using multiple-resonant equalization," *IEEE Photonics Technol. Lett.*, vol. 20, no. 14, pp. 1243–1245, 2008.
- [9] D. O'Brien, R. Turnbull, H. Le Minh, G. Faulkner, O. Bouchet, P. Porcon, M. El Tabach, E. Gueutier, M. Wolf, L. Grobe, and J. Li, "High-speed optical wireless demonstrators: Conclusions and future directions," *J. Light. Technol.*, vol. 30, no. 13, pp. 2181–2187, 2012.
- [10] D. C. O'Brien, G. E. Faulkner, E. B. Zyambo, K. Jim, D. J. Edwards, P. Stavrinou, G. Parry, J. Bellon, M. J. Sibley, V. A. Lalithambika, V. M. Joyner, R. J. Samsudin, D. M. Holburn, and R. J. Mears, "Integrated transceivers for optical wireless communications," *IEEE J. Sel. Top. Quantum Electron.*, vol. 11, no. 1, pp. 173–183, 2005.
- [11] Z. Chen, D. Tsonev, and H. Haas, "Improving SINR in indoor cellular visible light communication networks," in *2014 IEEE International Conference on Communications, ICC 2014*, 2014, no. 1, pp. 3383–3388.
- [12] J. Li, X. Huang, and N. Chi, "Enhanced performance of single-input multiple-output visible light communication system utilizing space diversity technology," *Opt. Eng.*, vol. 54, no. 3, p. 036109, Mar. 2015.
- [13] A. Burton, Z. Ghassemlooy, S. Rajbhandari, and S.-K. Liaw, "Design and analysis of an angular-segmented full-mobility visible light communications receiver," *Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 6, pp. 591–599, Jun. 2014.
- [14] J. F. Li, Z. T. Huang, R. Q. Zhang, F. X. Zeng, M. Jiang, and Y. F. Ji, "Superposed pulse amplitude modulation for visible light communication," *Opt. Express*, vol. 21, no. 25, pp. 31006–31011, 2013.
- [15] J. Hermsdorf, J. J. D. Mckendry, R. Ferreira, R. Henderson, S. Videv, S. Watson, H. Haas, A. E. Kelly, E. Gu, and M. D. Dawson, "Single-chip discrete multitone generation," in *Summer Topicals Meeting Series (SUM)*, 2015, vol. 2, pp. 47–48.
- [16] X. Li, N. Bamiedakis, J. L. Wei, J. J. D. Mckendry, E. Xie, R. Ferreira, and E. Gu, "6.25 Gb/s POF Link Using GaN μ LED Array s and Optically Generated Pulse Amplitude Modulation," no. c, pp. 15–16, 2015.
- [17] A. Yang, "Grouped Modulation Scheme for LED Array Module in a Visible Light Communication System," *IEEE Wirel. Commun.*, no. April, pp. 24–28, 2015.
- [18] M. S. A. Mossaad and S. Hrnilovic, "Practical OFDM signalling for visible light communications using spatial summation," *2014 27th Bienn. Symp. Commun. QBSC 2014*, pp. 5–9, 2014.
- [19] B. Yu, H. Zhang, L. Wei, and J. Song, "Subcarrier Grouping OFDM for Visible-Light Communication Systems," *IEEE Photonics J.*, vol. 7, no. 5, pp. 1–12, 2015.
- [20] T. Fath and H. Haas, "Optical spatial modulation using colour LEDs," *2013 IEEE Int. Conf. Commun.*, pp. 3938–3942, 2013.
- [21] W. O. Popoola and H. Haas, "Demonstration of the merit and limitation of generalised space shift keying for indoor visible light communications," *J. Light. Technol.*, vol. 32, no. 10, pp. 1960–1965, 2014.
- [22] M. Ijaz, D. Tsonev, J. J. D. McKendry, E. Xie, S. Rajbhandari, H. Chun, G. Faulkner, E. Gu, M. D. Dawson, D. O'Brien, and H. Haas,

- “Experimental proof-of-concept of optical spatial modulation OFDM using micro LEDs,” in *2015 IEEE International Conference on Communication Workshop, ICCW 2015*, 2015, vol. 2, pp. 1338–1343.
- [23] K. Cai and M. Jiang, “SM/SPPM Aided Multiuser Precoded Visible Light Communication Systems,” *IEEE Photonics J.*, vol. 8, no. 2, pp. 1–9, 2016.
- [24] K. D. Dambul, D. O’Brien, and G. Faulkner, “Indoor Optical Wireless MIMO System With an Imaging Receiver,” *IEEE Photonics Technol. Lett.*, vol. 23, no. 2, pp. 97–99, 2011.
- [25] A. Burton, H. Minh, Z. Ghassemlooy, E. Bentley, and C. Botella, “Experimental demonstration of 50-Mbps visible light communications using 4 × 4 MIMO,” *IEEE Photonics Technol. Lett.*, vol. 26, 2014.
- [26] D. O’Brien, “Optical Multi-Input Multi-Output systems for short-range free-space data transmission,” *Communication Systems Networks and Digital Signal Processing (CSNDSP), 2010 7th International Symposium on*, pp. 517–521, 2010.
- [27] S.-M. Kim and J.-B. Jeon, “Experimental Demonstration of 4x4 MIMO Wireless Visible Light Communication Using a Commercial CCD Image Sensor,” *J. Inf. Commun. Converg. Eng.*, vol. 10, no. 3, pp. 220–224, 2012.
- [28] A. H. Azhar, T. Tran, and D. C. O’Brien, “A Gigabit/s Indoor Wireless Transmission Using MIMO-OFDM Visible-Light Communications,” *IEEE Photonics Technol. Lett.*, vol. 25, no. 2, pp. 171–174, 2013.
- [29] S. Rajbhandari, H. Chun, G. Faulkner, K. Cameron, A. V. N. Jalajakumari, R. Henderson, D. Tsonev, M. Ijaz, Z. Chen, H. Haas, E. Xie, J. J. D. McKendry, J. Herrnsdorf, E. Gu, M. D. Dawson, and D. O’Brien, “High-speed integrated visible light communication system: Device constraints and design considerations,” *IEEE J. Sel. areas Commun.*, vol. 33, no. 9, pp. 1750–1757, 2015.
- [30] J. M. Kahn, P. Djahani, A. G. Weisbin, K. T. Beh, A. P. Tang, R. You, P. Djahani, A. G. Weisbin, B. K. Teik, and A. P. Tang, “Imaging diversity receivers for high-speed infrared wireless communication,” *IEEE Commun. Mag.*, vol. 36, no. 12, pp. 88–94, 1998.
- [31] Y. Jiang, M. K. Varanasi, and J. Li, “Performance Analysis of ZF and MMSE Equalizers for MIMO Systems: An In-Depth Study of the High SNR Regime,” *IEEE Trans. Inf. Theory*, vol. 57, no. 4, pp. 2008–2026, 2011.
- [32] G. Ginis and J. M. Cioffi, “On the relation between V-BLAST and the GDFE,” *Commun. Lett. IEEE*, vol. 5, no. 9, pp. 364–366, 2001.
- [33] T. Fath and H. Haas, “Performance comparison of MIMO techniques for optical wireless communications in indoor environments,” *IEEE Trans. Commun.*, vol. 61, 2013.
- [34] P. M. Butala, H. Elgala, and T. D. C. Little, “Performance of optical spatial modulation and spatial multiplexing with imaging receiver,” in *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*, 2014, pp. 394–399.
- [35] W. Yuanquan, C. Nan, Y. Wang, and N. Chi, “Demonstration of High-Speed 2x2 Non-Imaging MIMO Nyquist Single Carrier Visible Light Communication With Frequency Domain Equalization,” *Light. Technol. J.*, vol. 32, no. 11, pp. 2087–2093, 2014.
- [36] Y. W. Yuanquan Wang and N. C. Nan Chi, “Indoor gigabit 2 × 2 imaging multiple-input-multiple-output visible light communication,” *Chinese Opt. Lett.*, vol. 12, no. 10, pp. 100603–100606, 2014.
- [37] P. A. Haigh, Z. Ghassemlooy, I. Papakonstantinou, F. Tedde, S. F. Tedde, O. Hayden, and S. Rajbhandari, “A MIMO-ANN system for increasing data rates in organic visible light communications systems,” in *Communications (ICC), 2013 IEEE International Conference on*, 2013, pp. 5322–5327.
- [38] Z. Shuailong, S. Watson, J. J. D. McKendry, D. Massoubre, A. Cogman, G. Erdan, R. K. Henderson, A. E. Kelly, and M. D. Dawson, “1.5 Gbit/s Multi-Channel Visible Light Communications Using CMOS-Controlled GaN-Based LEDs,” *J. Light. Technol.*, vol. 31, no. 8, pp. 1211–1216, 2013.
- [39] T. Chen, L. Liu, Z. Zheng, J. Song, K. Wu, and W. Hu, “Fisheye-lens-based space division multiplexing system for visible light communications,” *EURASIP J. Wirel. Commun. Netw.*, vol. 2015, no. 1, pp. 1–7, 2015.
- [40] S. Rajbhandari, A. V. N. Jalajakumari, H. Chun, G. Faulkner, K. Cameron, R. Henderson, D. Tsonev, H. Haas, E. Xie, J. J. D. McKendry, J. Herrnsdorf, R. Ferreira, E. Gu, M. D. Dawson, and D. O’Brien, “A 7 Gbps Integrated Multiple Input Multiple Output Visible Light Communication Demonstrator,” *J. Light. Technol.*, 2016.
- [41] D. Tsonev, S. Videv, and H. Haas, “Towards a 100 Gb/s visible light wireless access network,” *Opt. Express*, vol. 23, no. 2, pp. 1627–1637, 2015.
- [42] P. Manousiadis, C. Hyunchae, S. Rajbhandari, R. Mulyawan, D. A. Vithanage, G. Faulkner, D. Tsonev, J. J. D. McKendry, M. Ijaz, X. Enyuan, E. Gu, M. D. Dawson, H. Haas, G. A. Turnbull, I. D. W. Samuel, and D. O’Brien, “Demonstration of 2.3 Gb/s RGB white-light VLC using polymer based colour-converters and GaN micro-LEDs,” in *Summer Topicals Meeting Series (SUM), 2015*, 2015, pp. 222–223.
- [43] J. Vucic, C. Kottke, K. Habel, and K.-D. Langer, “803 Mbit/s visible light WDM link based on DMT modulation of a single RGB LED luminary,” in *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*, 2011, pp. 1–3.
- [44] G. Cossu, W. Ali, R. Corsini, and E. Ciaramella, “Gigabit-class optical wireless communication system at indoor distances (1.5 ÷ 4 m),” *Opt. Express*, vol. 23, no. 12, pp. 15700–15705, 2015.
- [45] Y. Wang, L. Tao, X. Huang, J. Shi, and N. Chi, “Enhanced Performance of a High-Speed WDM CAP64 VLC System Employing Volterra Series-Based Nonlinear Equalizer,” *IEEE Photonics J.*, vol. 7, no. 3, pp. 1–7, 2015.
- [46] B. Janjua, H. M. Oubei, J. R. D. Retamal, T. K. Ng, C.-T. Tsai, H.-Y. Wang, Y.-C. Chi, H.-C. Kuo, G.-R. Lin, J.-H. He, and B. S. Ooi, “Going beyond 4 Gbps data rate by employing RGB laser diodes for visible light communication,” *Opt. Express*, vol. 23, no. 14, pp. 18746–18753, 2015.
- [47] D. Tsonev, H. Chun, S. Rajbhandari, J. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. Kelly, G. Faulkner, M. Dawson, H. Haas, and D. O’Brien, “A 3-Gb/s single-LED OFDM-based wireless VLC link using a Gallium Nitride μ LED,” *IEEE Photonics Technol. Lett.*, vol. 26, no. 7, pp. 637–640, 2014.
- [48] Y.-C. Chi, D.-H. Hsieh, C.-T. Tsai, H.-Y. Chen, H.-C. Kuo, and G.-R. Lin, “450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM,” *Opt. Express*, vol. 23, no. 10, pp. 13051–13059, 2015.
- [49] H. Chun, S. Rajbhandari, D. Tsonev, G. Faulkner, H. Haas, and D. O’Brien, “Visible light communication using laser diode based remote phosphor technique,” in *Communication Workshop (ICCW), 2015 IEEE International Conference on*, 2015, pp. 1392–1397.
- [50] J. J. D. McKendry, R. P. Green, A. E. Kelly, G. Zheng, B. Guilhabert, D. Massoubre, E. Gu, and M. D. Dawson, “High-speed visible light communications using individual pixels in a micro light-emitting diode array,” *IEEE Photonics Technol. Lett.*, vol. 22, no. 18, pp. 1346–1348, 2010.
- [51] S. Collins, D. C. O’Brien, and A. Watt, “High gain, wide field of view concentrator for optical communications,” *Opt. Lett.*, vol. 39, no. 7, pp. 1756–1759, 2014.
- [52] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, “3.4 Gbit/s visible optical wireless transmission based on RGB LED,” *Opt. Express*, vol. 20, 2012.
- [53] M. I. Olmedo, T. Zuo, J. B. Jensen, Q. Zhong, X. Xu, S. Popov, and I. T. Monroy, “Multiband carrierless amplitude phase modulation for high capacity optical data links,” *J. Light. Technol.*, vol. 32, no. 4, pp. 798–804, 2014.
- [54] X. Huang, S. Chen, Z. Wang, J. Shi, Y. Wang, J. Xiao, and N. Chi, “2.0-Gb/s Visible Light Link Based on Adaptive Bit Allocation OFDM of a Single Phosphorescent White LED,” *IEEE Photonics J.*, vol. 7, no. 5, pp. 1–8, 2015.
- [55] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, “1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation,” *IEEE Photonics J.*, vol. 4, no. 5, pp. 1465–1473, 2012.
- [56] G. Stepniak, J. Siuzdak, and P. Zwierko, “Compensation of a VLC Phosphorescent White LED Nonlinearity by Means of Volterra DFE,” *IEEE Photonics Technol. Lett.*, vol. 25, no. 16, pp. 1597–1600, 2013.
- [57] T. Chen, L. Liu, B. Tu, Z. Zheng, and W. Hu, “High-spatial-diversity imaging receiver using fisheye lens for indoor MIMO VLCs,” *IEEE Photonics Technol. Lett.*, vol. 26, 2014.