Research Article | Vol. 27, No. 21 / 14 October 2019 / Optics Express 30788

Optics EXPRESS

Low complexity OFDM VLC system enabled by spatial summing modulation

YANBING YANG,[1] CHEN CHEN,[2,*] PENGFEI DU,[3] XIONG DENG,[4] JUN LUO,[5] WEN-DE ZHONG,[6] AND LIANGYIN CHEN[1]

[1] *College of Computer Science, Sichuan University, Chengdu, 610065, China*
[2] *School of Microelectronics and Communication Engineering, Chongqing University, Chongqing, 400044, China*
[3] *A*STAR's Singapore Institute of Manufacturing Technology (SIMTech), 138634, Singapore*
[4] *Department of Electrical Engineering, Eindhoven University of Technology (TU/e), Flux Building,5600MB Eindhoven, Netherlands*
[5] *School of Computer Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore*
[6] *School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore*
[*] *c.chen@cqu.edu.cn*

Abstract: Commercial-off-the-shelf (COTS) devices enabled visible light communication (VLC) for Internet of things (IoT) applications has attracted extensive attentions from both academic and industrial communities, thanks to the pervasive deployments of light emitting diode (LED) lighting infrastructure. However, due to the limitation of frequency response and non-linearity of the commercial illuminating LED light consisting of multiple LED chips, the achievable data rate is far less than that provided by the experimental VLC system with a single LED with specialized devices, e.g., lens. To this end, we propose a power-of-2 arrangement scheme for LED chips to generate spatial summing modulation with low control complexity, and demonstrate its availability in an orthogonal frequency division multiplexing (OFDM) VLC system purely built upon COTS devices. It significantly differs from a conventional OFDM VLC system relying on digital-to-analog converter (DAC) and analog signal chain, which is complex and confined by LED's non-linearity, thanks to we design a novel digital-to-light converter (DLC) which can output 256 light intensities linearly and be directly controlled by the discrete digital signals generated by the OFDM modulator. An experimental demonstration with employing the QAM-OFDM modulation scheme successfully confirms the effectiveness of the proposed spatial summing VLC system, which can achieve low BERs of below the forward error correct (FEC) threshold of 3.8×10^{-3} for both QAM8 and QAM16 running transmission frequency of 300 kHz under a communication distance of 0.8 m. It demonstrates the promising potential for delivering a data rate at hundred kbps level with this novel spatial summing based OFDM VLC system, which is sufficient for many IoT applications.

1. Introduction

With the booming grows of Internet of Things (IoT) devices, the generated huge sensed data is far beyond the capacity of existing radio-frequency (RF) communication techniques. Visible Light Communication (VLC) has been considered as an alternative to transport the massive sensing data produced by ubiquitous IoT nodes [1], thanks to its free spectrum resource, high energy-efficiency, reusing lighting infrastructure and hence low cost [2]. In a typical VLC system, the commonly used white light-emitting diodes (LEDs) are envisioned as transmitters due to they can work for both illuminating and data transmission simultaneously. However, the white illuminating LED has strong non-linearity [3,4] and relatively low frequency response [5–7] due

#376312 https://doi.org/10.1364/OE.27.030788
Journal © 2019 Received 26 Aug 2019; revised 20 Sep 2019; accepted 20 Sep 2019; published 9 Oct 2019

Optics EXPRESS

to the phosphor cover, and most of existing works hence have to employ complicated processing circuits/algorithms to overcome the non-linearity [5,6,8–10], or simple modulation schemes, e.g., on-off keying (OOK) modulation, while at a cost of sacrificing spectral efficiency.

In order to mitigate the LED non-linearity and improve the spectral efficiency, spatial summing (or grouped) modulation has been proposed in [11–13] for single carrier VLC systems recently. Spatial summing modulation can directly generate discrete light intensities which represent signal symbols by controlling the number of alight LED chips in an LED array with only "on"/"off" logic. This concise control logic alleviates the linearity constraints of the illuminating LED chips. Comparing with the single carrier VLC systems [11,14,15], orthogonal frequency division multiplexing (OFDM) based VLC systems are immune to baseline wander and low frequency interference from ambient light. Besides, the inherent supporting for multiuser access of OFDM further reinforces its advantages to be a promising technology for VLC systems.

Using the spatial summing modulation scheme to generate OFDM signals without the bother of LED non-linearity is exactly feasible and cost-effective. For example, Thilo et al. proposed and implemented an optical transmitter with grouped infrared LEDs to transmit OFDM signals [16]. In [17], Mohammed et al. detailedly studied to use spatial summing modulation for suppressing the high peak-to-average power ratio (PAPR) in OFDM based VLC, and proposed to partition high PAPR OFDM signals into many low-PAPR narrowband signals which were transmitted by grouped LED chips individually. To evaluate the availability of spatial summing modulation in a real OFDM VLC system, most recently the authors of [18] implemented a prototype consisting of a 16×16 CMOS-integrated GaN LED array to realize discrete-level OFDM with spatial summing modulation, and achieved a spectral efficiency of 3.96 bits/s/Hz. However, those existing works do not investigate the feasibility of employing commercial white LEDs with spatial summing modulation for OFDM enabled VLC, while VLC systems are envisioned to piggyback on lighting infrastructure built upon commercial off-the-shelf (COTS) white LEDs. We summarize their proposals in Table 1 to highlight our contributions.

Table 1. Summary of spatial summing based VLC systems.

	LEDs	Signals	Resolutions	Modulation	Lens	Distance
[12]	3 white LEDs	3	2 bit	PAM	Y	0.6 m
[15]	16 white LEDs	16	4 bit	PAM	Y	0.5 m
[16]	36 IR LEDs	6	5 bit	QAM OFDM	N	7 m
[18]	256 GaN LEDs	256	5 bit	QAM OFDM	Y	0.03 m
Our work	256 white LEDs	8	8 bit	QAM OFDM	N	0.8 m

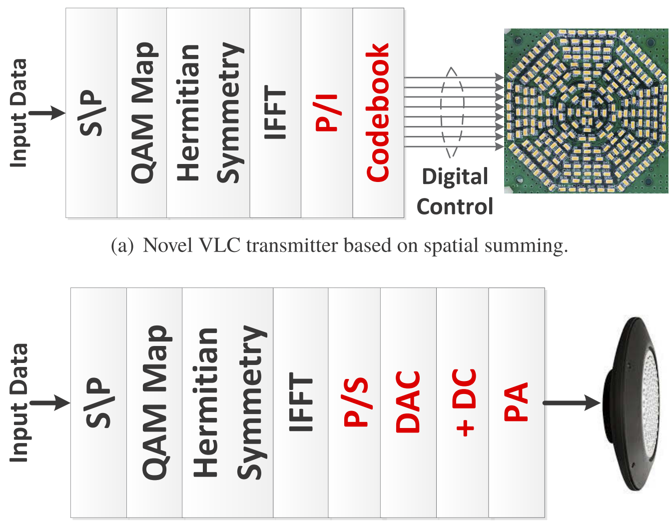
To this end, we propose a practical and cost-effective OFDM VLC system based on spatial summing modulation, and experimentally demonstrate its effectiveness. We innovatively arrange 255 LED chips with power-of-2 distribution on a disk face, so that on one hand ensures the output linearity, on the other hand, follows the control logic of an 8-bit conventional digital-to-analog converter (DAC) controlled by only 8 control signals, which can be conveniently used in an existing OFDM VLC system to replace the conventional DAC, bias-T and LED driver circuits. Extensive experiments strongly confirm the availability of the proposed transmitter enabled by spatial summing modulation, and it achieves promising bit error rate (BER) of 1.7×10^{-3} and 7.1×10^{-3} with QAM16 and QAM32 modulations in OFDM VLC under a frequency of 300 kHz at a 0.4m distance, respectively.

2. Spatial summing based OFDM VLC system

In this section, we first describe the system overview of the proposed spatial summing enabled OFDM VLC system while comparing it with a conventional OFDM VLC system. Figure 1(a)

Optics EXPRESS

depicts the novel spatial summing based OFDM VLC transmitter, while the architecture of a conventional transmitter is also illustrated in Fig. 1(b) as an intuitive comparison. To keep the simplicity, we omit to present the receiver in OFDM VLC in this paper, but rather refer the readers to Fig. 1 in [19]. In the OFDM VLC transmitter, the serial data stream is first converted to parallel data through serial-to-parallel (S/P) conversion as shown in Fig. 1. Subsequently, the parallel data is mapped to quadrature amplitude modulation (QAM) symbols and Hermitian symmetry is imposed to generated LED-compatible real-valued signal. Then, the inverse fast Fourier transform (IFFT) is performed. And the fundamental difference between spatial summing based transmitter and the conventional one comes here.



(a) Novel VLC transmitter based on spatial summing.

(b) Traditional VLC transmitter.

Fig. 1. System block diagrams of two different VLC transmitters.

The conventional transmitter converts the parallel to serial data and then driving a DAC to generate an analog electronic signal. To modulate the LED transmitter, a DC bias current and Power Amplification (PA) are further needed so as to obtain a sufficient unipolar driving current to modulate an illuminating LED. To mitigate the distortion caused by LED non-linearity to the modulated signal, complex pre-distortion circuitry is involved in many existing proposals [20,21]. However, the novel spatial summing enabled transmitter has much simpler control logic compared to the traditional one. Again as shown in Fig. 1(a), the parallel data is processed first to obtain the control index with customizable quantitative resolution via a block of P/I, where our current design supports up to a resolution of 8 bit as detailed in following section 3. The resulted index is used for looking up a pre-defined table which is corresponding with the transmitter. The generated code (digital control signal) will directly switch on or off the LED groups so as to produce expected modulated intensity. Intuitively, this spatial summing based transmitter has much lower complexity in terms of both hardware implementation and software control procedure. More importantly, it eliminates the impact of LED non-linearity due to only on-off control for LED chips in essential.

3. Prototype and experimental setup

In order to evaluate the performance of the proposed VLC system enabled by spatial summing modulation, we build a proof-of-concept prototype of the novel transmitter, and the testbed is shown in Fig. 2. We build the proposed transmitter that consists of low cost COTS white

Optics EXPRESS

illuminating LED chips of LUXEON 3014 with color temperature of 3000K. The transmitter front-end carries 255 LED chips which are divided into 8 groups, where the $i-th$ group includes 2^i chips (where, $i = 0, 1, \cdots, 7$). To be more specific, we put the first group of one LED chip at the center of transmitter and the last group with 128 LED chips at the periphery. Therefore, it can largely reduce the control complexity because only 8 digital control signals are needed to modulate the 255 LED chips and meanwhile guarantee the output linearity by fully leveraging the benefit of spatial distribution of LED chips, comparing with the existing works of [16,18] which used current-limiting cumbersome resistors to fine tune the output light intensity. To drive the LED chip groups, one or multiple low cost transistors of MMSS8050 according to the driving current are used thanks to its simple driving circuitry. We use a Xlinx FPGA to load the transmitting QAM-OFDM data-stream produced by MATLAB on a PC and generate the digital control signal for light modulation. Here, we make the sampling rate as an adjustable parameter which will be evaluated as transmission frequency (T_f) in Section 4. The FFT/IFFT size is 256 and totally 64 (2nd to 65th) subcarriers are used to transmit valid data. Hence, the bandwidth of the QAM-OFDM signal is given by $(300 \times 64)/256 = 75$ kHz. Since the multipath-induced ISI is generally negligible in typical VLC systems, no CP is used. Therefore, the data rate is given by $75 \times (log_2 M)$ bits/s, where M is the order of QAM constellation, and the spectral efficiency is given by $(log_2 M) \times 64/256 = (log_2 M)/4$ bits/s/Hz. Each experiment includes 50 sessions and each session includes the transmission of 200 OFDM symbols, and we report the average results over all sessions. The designed transmitter works at a power supply of 12V similar to a common COTS LED light bulb and consumes a driving current of around 0.5A by the whole transmitter. It is able to emit an intensity of 400 lux at a distance of 1.2 m, which meets the illumination requirement for normal home environment. At the receiver side, a photodiode of Thorlabs PDA36A is used to capture the modulated light and converts the light signal to electronic signal. And the PDA36A's output is recorded by an oscilloscope, and processed in MATLAB on a PC.

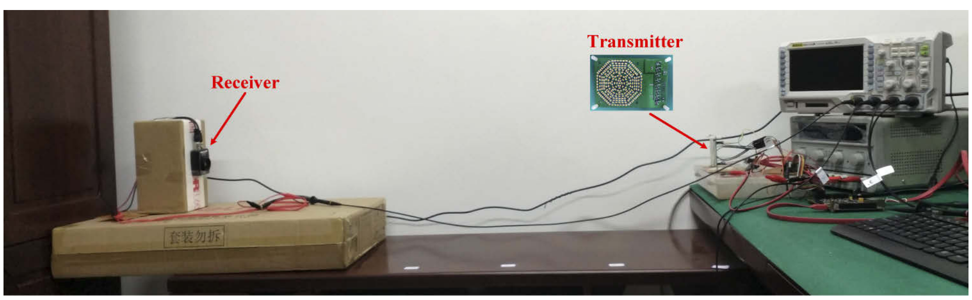


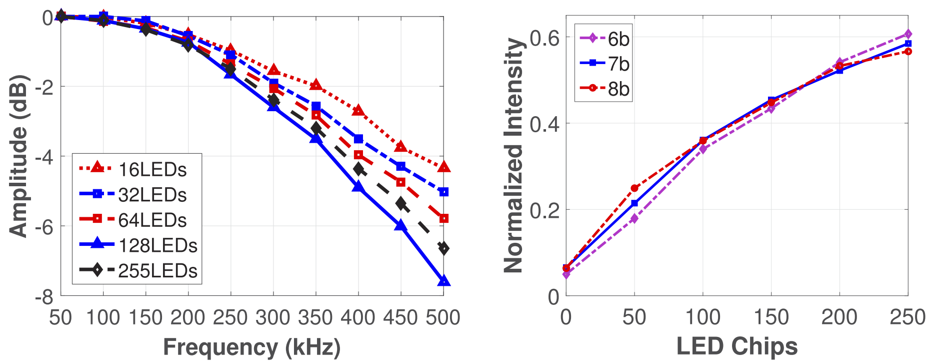
Fig. 2. Experimental testbed with the novel LED transmitter.

4. Results and discussions

We evaluate the performance of the proposed spatial summing based OFDM VLC system via extensive experiments under various experimental settings, and seriously discuss the experiment results to better understand the limitations and potentials of this novel technique. Since the superiority of spatial summing modulation comparing to the VLC system with a traditional transmitter shown in Fig. 1(b) has been directly verified in [12], we omit to report the comparison result in this paper but focus on the communication performance.

4.1. Frequency response and output linearity

To quickly examine the performance of the novel transmitter enabled by spatial summing, we firstly test the frequency response and output linearity in this section. Although the 3-dB modulation bandwidth of a single COTS illuminating LED can be up to several MHz [3,5], it reduces to around 350 KHz for grouped LEDs as illustrated in Fig. 3(a) due to the connections of LEDs and driving transistors, which is in line with the observation in [13,18]. It is intuitive to be observed that the larger group with more LED chips has slightly lower running frequency due to the more LED chips in one group have relatively complex wiring connection with each other which delays the control signal. Anyway, the novel transmitter can support a safe frequency over 300 kHz, which can deliver a sufficient data rate at hundred kbps level for many IoT applications.



(a) Frequency response (b) Output linearity

Fig. 3. The frequency response and output linearity of the proposed transmitter.

We also investigate the output performance of the spatial summing based transmitter through measuring the output light intensity. Figure 3(b) reports the experiment results. As we could expect, the output is almost linear within the full dynamic range of the transmitter, which is much wider than the narrow linear zone used in traditional LED transmitter reported in existing works [22,23]. And the tiny non-linearity caused by chip diversity could be further corrected by slightly adjust the current-limiting resistor [16]. Anyway, the current prototype clearly shows its superiority of the proposed transmitter in this paper compared to existing designs, and reveals the potential for transmitting higher order modulation with larger dynamic range, which will be reported in following section via more experiments.

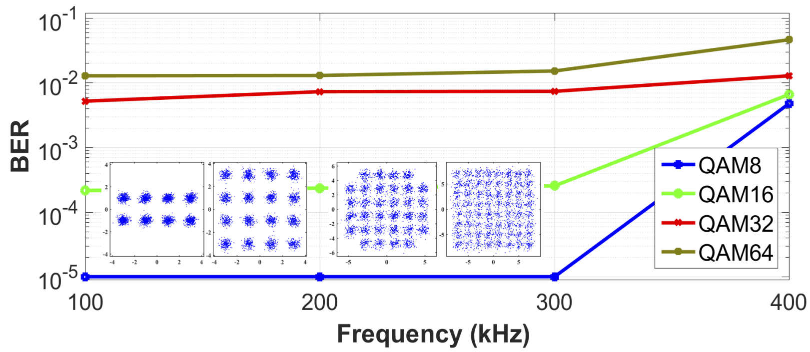
4.2. BER vs. transmission frequency

In this section we detailedly examine its performance in terms of bit error rate (BER) under a varying transmission frequency. To as far as possible probe the limits of the implemented prototype, we adopt different order of M-ary QAM constellations, i.e., QAM8, QAM16, QAM32 and QAM64, to generate the OFDM data stream, and the OFDM waveform is further quantized into different resolutions of 6, 7 and 8 bits to obtain the index for looking up the codebook as described in Section 2. Here, a maximum quantization resolution of 8 bits is chosen thanks to our current prototype can emit 256 light intensities with 8 control signals as mentioned in Section 3. We fix the receiver at a distance of 0.4 m away from the transmitter, and vary the transmission frequency ranging from 100 kHz to 400 kHz. Figure 4 graphically presents the experiment results, and we also draw the obtained constellation diagrams for each modulation scheme under a transmission frequency of 300 kHz in the figure. It is to be expected that two lower order modulation schemes of QAM8 and QAM16 achieve lower BER in all tests thanks to their relatively larger symbol distance immunizing to noises comparing with the higher order modulations of QAM32 and QAM64. To be more specific, the quantization error has limited impact on the BER performance, and the results clearly show that a proper quantization resolution may improve the BER. Agreed with the early work of [18] which revealed the performance saturates for highest bit resolution due to the increased nonlinearity, so in our test the properly low 6 bit resolution has the best performance thanks to the larger quantization step space. We also directly present the comparison under different quantization resolutions to intuitively illustrate the experiment results as shown in Fig. 5. But it is still worth to chase higher quantization resolution to support higher order modulation such as QAM128, and we leave it as a future work by implementing a more advanced prototype. Nevertheless, our current prototype with spatial summing technique can achieve a BER lower than the forward error correct (FEC) threshold of 3.8×10^{-3} for both QAM8 and QAM16 at a maximum frequency of 300 kHz, which demonstrates its promising potentials for delivering a hundred kbps level data rate with COTS illuminating LEDs without lens.

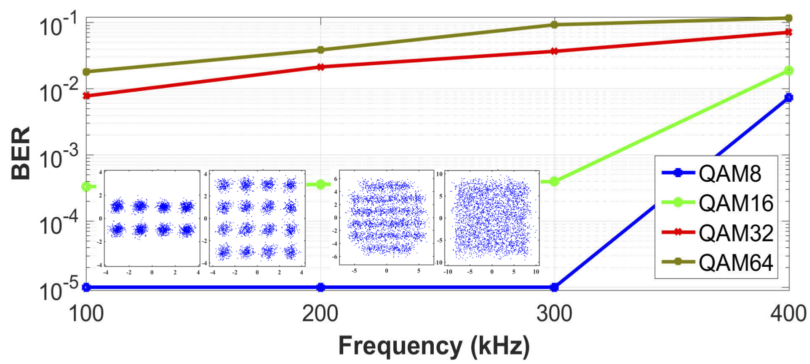
4.3. BER vs. distance

In this section, we test the BER performance under a varying distance and change the distance between the transmitter and receiver from 0.4 m to 1.2 m. To achieve reasonable BER results, we configure the transmission frequency at 300 kHz and adopt QAM8 and QAM16 modulation scheme thanks to their superior performance comparing with QAM32 and QAM64 as reported in former subsection. As shown in Fig. 6, as we could expect that QAM8 always outperform QAM16 in terms of BER thanks to its larger symbol distance in constellation. Fortunately, both QAM8 and QAM16 achieve the BER of below 3.7×10^{-3} at a maximum distance of 0.8 m. To be more specific, the quantization resolution has slightly obvious impact on the BER performance under a closed distance within the communication range of 0.8 m, and the 6 bit resolution always has the best performance which is in line with the results in former section of 4.2. It is understood that the BER seriously degrades under a larger distance beyond 0.8 m due to the achieved SNR is too low for demodulating, but the communication distance can be largely extended if a lens or cone shaped cover was adopted for improving the SNR. Even so, the experiment results obtained by our current prototype demonstrate its feasibility and effectiveness to deliver hundred kbps level data rate at a distance of 0.8 m by the practical OFDM VLC system purely built upon COTS devices.

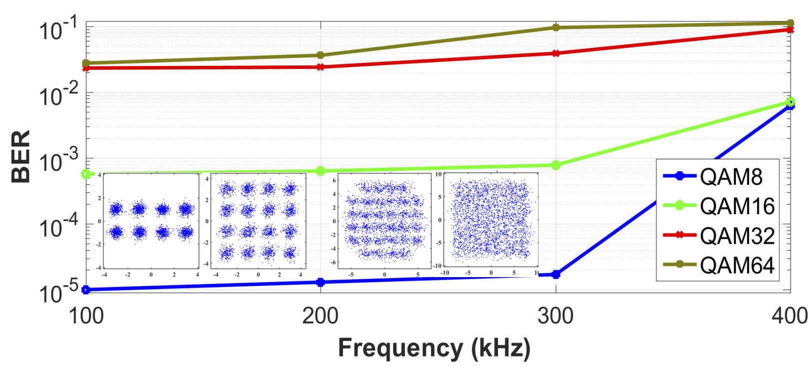
Optics EXPRESS



(a) With a quantization resolution of 6 bits.



(b) With a quantization resolution of 7 bits.



(c) With a quantization resolution of 8 bits.

Fig. 4. Measured BER under different transmission frequency and quantization resolutions.

Optics EXPRESS

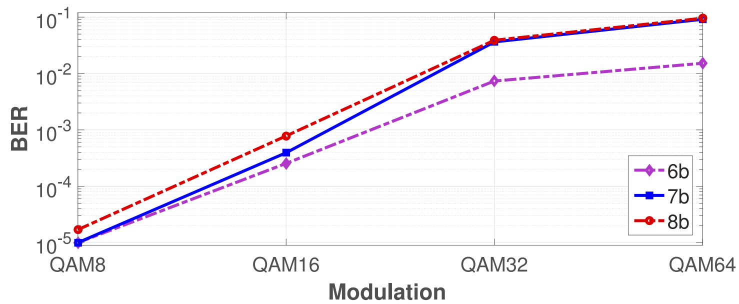


Fig. 5. Performance comparison under different quantization resolutions.

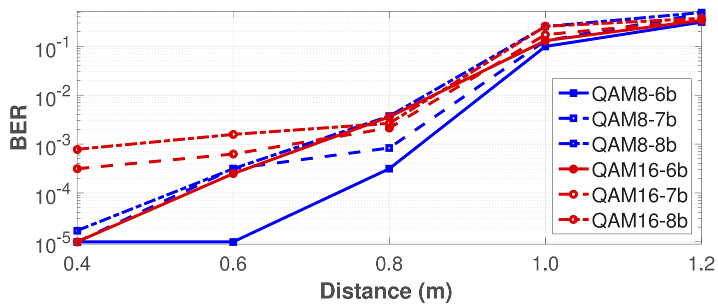


Fig. 6. Measured BER versus various communication distance.

5. Conclusion

In order to push the VLC technology into practical IoT applications, in this paper, a novel spatial summing based OFDM VLC system purely built on COTS devices is presented. Essentially, we propose a novel idea of grouping the LED chips on the transmitter and arranging them with power-of-2 distribution on a disk face so that can directly output linear 256 light intensities with only 8 digital control signals but without the bother of LED non-linearity. By implementing a delicate yet low cost prototype, we have demonstrated the feasibility and promising performance of using spatial summing for an OFDM VLC system. Experiment results show our current prototype can achieve very low BERs of below the FEC threshold of 3.8×10^{-3} for both QAM8 and QAM16 at a maximum transmission frequency of 300 kHz under a maximum communication distance of 0.8 m, and it reveals the promising potential for delivering a data rate at hundred kbps level which is suitable for many IoT applications.

Funding

Fundamental Research Funds for the Central Universities (YJ201868); National Natural Science Foundation of China (61901065, 61902267).

References

1. I. Demirkol, D. Camps-Mur, J. Paradells, M. Combalia, W. Popoola, and H. Haas, “Powering the internet of things through light communication,” IEEE Commun. Mag. **57**(6), 107–113 (2019).
2. J.-Y. Sung, C. Chow, and C.-H. Yeh, “Dimming-discrete-multi-tone (dmt) for simultaneous color control and high speed visible light communication,” Opt. Express **22**(7), 7538–7543 (2014).
3. C.-H. Yeh, Y.-L. Liu, and C.-W. Chow, “Real-time thite-light phosphor-LED visible light communication (VLC) with compact Size,” Opt. Express **21**(22), 26192–26197 (2013).
4. K. Ying, Z. Yu, R. J. Baxley, H. Qian, G.-K. Chang, and G. T. Zhou, “Nonlinear distortion mitigation in visible light communications,” IEEE Wireless Commun. **22**(2), 36–45 (2015).

Optics EXPRESS

5. C. H. Yeh, C. W. Chow, Y. F. Liu, and P. Y. Huang, "Simple digital fir equalizer design for improving the phosphor led modulation bandwidth in visible light communication," Opt. Quantum Electron. **45**(8), 901–905 (2013).
6. C. Hsu, C. Chow, I. Lu, Y. Liu, C. Yeh, and Y. Liu, "High speed imaging 3×3 mimo phosphor white-light led based visible light communication system," IEEE Photonics J. **8**(6), 1–6 (2016).
7. J.-Y. Sung, C. Chow, and C.-H. Yeh, "Is blue optical filter necessary in high speed phosphor-based white light led visible light communications?" Opt. Express **22**(17), 20646–20651 (2014).
8. H. Elgala, R. Mesleh, and H. Haas, "Non-Linearity effects and predistortion in optical OFDM wireless transmission Using LEDs," Inderscience Int. J. Ultra Wideband Commun. Syst. **1**(2), 143–150 (2009).
9. H. Qian, S. Yao, S. Cai, and T. Zhou, "Adaptive postdistortion for nonlinear LEDs in visible light communications," IEEE Photonics J. **6**(4), 1–8 (2014).
10. X. Huang, Z. Wang, J. Shi, Y. Wang, and N. Chi, "1.6 Gbit/s phosphorescent white LED based VLC transmission using A cascaded pre-equalization circuit and A differential outputs PIN receiver," Opt. Express **23**(17), 22034–22042 (2015).
11. J. Du, W. Xu, H. Zhang, and C. Zhao, "Visible light communications using spatial summing pam with led array," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, (2017), pp. 1–6.
12. A. Yang, Y. Wu, M. Kavehrad, and G. Ni, "Grouped modulation scheme for led array module in a visible light communication system," IEEE Wireless Commun. **22**(2), 24–28 (2015).
13. Y. Yang, J. Luo, C. Chen, W.-D. Zhong, and L. Chen, "SynLight: synthetic light emission for fast transmission in COTS device-enabled VLC," in *Proc. of the 38th IEEE INFOCOM*, (2019), pp. 1–9.
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 **21**(25), 31006–31011 (2013).
15. C. Xi, A. Mirvakili, and V. J. Koomson, "A visible light communication system demonstration based on 16-level pulse amplitude modulation of an led array," in *2012 Symposium on Photonics and Optoelectronics*, (2012), pp. 1–4.
16. T. Fath, C. Heller, and H. Haas, "Optical wireless transmitter employing discrete power level stepping," J. Lightwave Technol. **31**(11), 1734–1743 (2013).
17. M. S. A. Mossaad, S. Hranilovic, and L. Lampe, "Visible light communications using ofdm and multiple leds," IEEE Trans. Commun. **63**(11), 4304–4313 (2015).
18. A. D. Griffiths, M. S. Islim, J. Herrnsdorf, J. J. D. McKendry, R. Henderson, H. Haas, E. Gu, and M. D. Dawson, "Cmos-integrated gan led array for discrete power level stepping in visible light communications," Opt. Express **25**(8), A338–A345 (2017).
19. C. Chen, W. Zhong, and L. Zhao, "Sparse bayesian rvm regression based channel estimation for im/dd ofdm-vlc systems with reduced training overhead," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, (2017), pp. 162–167.
20. R. Mesleh, H. Elgala, and H. Haas, "Led nonlinearity mitigation techniques in optical wireless ofdm communication systems," J. Opt. Commun. Netw. **4**(11), 865–875 (2012).
21. L. C. Mathias, J. C. M. Filho, and T. Abrao, "Predistortion and pre-equalization for nonlinearities and low-pass effect mitigation in ofdm-vlc systems," Appl. Opt. **58**(19), 5328–5338 (2019).
22. I. Stefan, H. Elgala, and H. Haas, "Study of dimming and led nonlinearity for aco-ofdm based vlc systems," in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, (2012), pp. 990–994.
23. H. Elgala, R. Mesleh, and H. Haas, "An led model for intensity-modulated optical communication systems," IEEE Photonics Technol. Lett. **22**(11), 835–837 (2010).