Modulation Techniques for Li-Fi

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Abstract

Modulation techniques for light fidelity (Li-Fi) are reviewed in this paper. Li-Fi is the fully networked solution for multiple users that combines communication and illumination simultaneously. Light emitting diodes (LEDs) are used in Li-Fi as visible light transmitters, therefore, only intensity modulated direct detected modulation techniques can be achieved. Single carrier modulation techniques are straightforward to be used in Li-Fi, however, computationally complex equalization processes are required in frequency selective Li-Fi channels. On the other hand, multicarrier modulation techniques offer a viable solution for Li-Fi in terms of power, spectral and computational efficiency. In particular, orthogonal frequency division multiplexing (OFDM) based modulation techniques offer a practical solution for Li-Fi, especially when direct current (DC) wander, and adaptive bit and power loading techniques are considered. Li-Fi modulation techniques need to also satisfy illumination requirements. Flickering avoidance and dimming control are considered in the variant modulation techniques presented. This paper surveys the suitable modulation techniques for Li-Fi including those which explore time, frequency and colour domains.

Keywords

light fidelity (Li-Fi); optical wireless communications (OWC); visible light communication (VLC); intensity modulation and direct detection (IM/DD); orthogonal frequency division multiplexing (OFDM)

1 Introduction

More than half a billion new communication devices were added to the network services in 2015. Globally, mobile data traffic is predicted to reach 30.6 exabytes per month by 2020 (the equivalent of 7641 million DVDs each month), up from 3.7 exabytes per month in 2015 [1]. The radio frequency bandwidth currently used is a very limited resource. The increasing dependency on cloud services for storage and processing means that new access technologies are necessary to allow this huge increase in network utilization. The visible light spectrum on the other hand offers a 10,000 times larger unlicensed frequency bandwidth that could accommodate this expansion of network capacity. Visible light communication (VLC) is the point-to-point high speed communication and illumination system. Light fidelity (Li-Fi) is the complete wireless, bi-directional, multi-user network solution for visible light communications that would operate seamlessly alongside other Long Term Evolution (LTE) and wireless fidelity (Wi-Fi) access technologies [2]. Li-Fi is a green communication method as it reuses the existing lightning infrastructure for communications. Information is transmitted by the rapid subtle changes of light intensity that is unnoticeable by the human eye. Recent studies have demonstrated data rates of 14 Gbps for Li-Fi using three off-the-shelf laser diodes (red, green and blue) [3]. It was also predict that a data rate of 100 Gbps is achievable for Li-Fi when the whole visible spectrum is utilized [3]. Li-Fi offers inherent security, and also it can be employed in areas where sensitive electronic devices are present, such as in hospitals. In addition, Li-Fi is a potential candidate for other applications such as underwater communications, intelligent transportation systems, indoor positioning, and the Internet of Things (IoT) [2].

Modulation techniques developed for intensity modulation and direct detection (IM/DD) optical wireless communication (OWC) systems are suitable for Li-Fi communications systems. However, these modulation techniques may not be suitable for all lightning regimes. Li-Fi transceivers are illumination devices enabled for data communications. Therefore adapting IM/DD modulation technique should first satisfy certain illumination requirements before being Li-Fi enabled. For example, modulation techniques should support dimmable illumination so that communication would be still available when the illumination is not required. Li-Fi uses off-the-shelf light emitting diodes (LEDs) and photodiodes (PDs) as channel front-end devices. This restricts signals propagating throughout the channel to
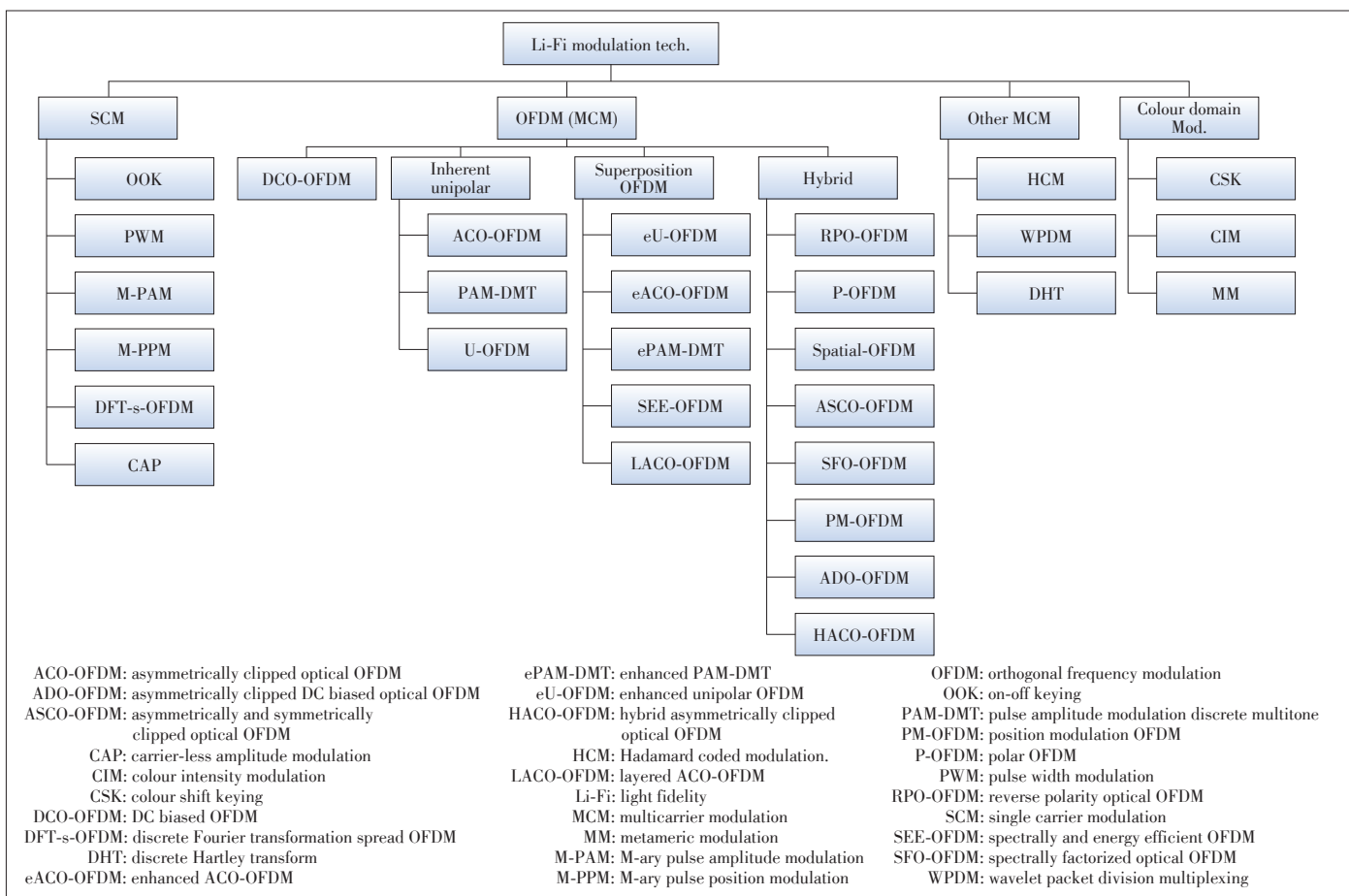
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strictly positive signals. Single carrier modulation (SCM) techniques are straight forward to implement in Li-Fi. Modulation techniques, such as on-off keying (OOK), pulse-position modulation (PPM), and M-ary pulse-amplitude modulation (M-PAM), can be easily implemented. However, due to the dispersive nature of optical wireless channels, such schemes require complex equalizers at the receiver. Therefore, the performance of these schemes degrades as their spectral efficiency (SE) increases. On the other hand, multiple carrier modulation (MCM) techniques, such as the orthogonal frequency division multiplexing (OFDM), have been shown to be potential candidates for optical wireless channels since they only require single tap equalizer at the receiver. Adaptive bit and power loading can maximize the achievable data rates of OFDM-based Li-Fi systems by adapting the system loading to the channel frequency response. Moreover, the DC wander and low frequency interference can be easily avoided in OFDM by optimizing the adaptive bit/power loading to avoid the low frequency subcarriers. Colour modulation techniques are unique to Li-Fi communication systems as the information is modulated on the instantaneous colour changes. The colour dimension adds a new degree of freedom to Li-Fi. The various modulation Li-Fi modulation techniques discussed in this paper are shown in **Fig. 1**.

This paper is organized as follows: The main challenges for Li-Fi modulation techniques are summarized in Section 2. SCM techniques for Li-Fi are detailed in Section 3. OFDM-based modulation techniques for Li-Fi are discussed in details in Section 4, including inherent unipolar OFDM techniques, hybrid OFDM modulation techniques and superposition OFDM modulation techniques. Other MCM techniques are revised in Section 5. The unique colour domain modulation techniques are discussed in Section 6. Finally the conclusion is presented in Section 7. The paper is limited to single input-single output (SISO) Li-Fi communication systems. The space dimension of Li-Fi is not considered in this paper.

2 Li-Fi Modulation Techniques Challenges

Li-Fi is an emerging high-speed, low-cost solution to the scarcity of the radio frequency (RF) spectrum, therefore it is expected to be realized using the widely deployed off-the-shelf optoelectronic LEDs. Due to the mass production of these inexpensive devices, they lack accurate characterizations. In Li-Fi, light is modulated on the subtle changes of the light intensity, therefore, the communication link would be affected by the nonlinearity of the voltage-luminance characteristic. As a solution,

ACO-OFDM: asymmetrically clipped optical OFDM
ADO-OFDM: asymmetrically clipped DC biased optical OFDM
ASCO-OFDM: asymmetrically and symmetrically
    clipped optical OFDM
CAP: carrier-less amplitude modulation
CIM: colour intensity modulation
CSK: colour shift keying
DCO-OFDM: DC biased OFDM
DFT-s-OFDM: discrete Fourier transformation spread OFDM
DHT: discrete Hartley transform
eACO-OFDM: enhanced ACO-OFDM

ePAM-DMT: enhanced PAM-DMT
eU-OFDM: enhanced unipolar OFDM
HACO-OFDM: hybrid asymmetrically clipped
    optical OFDM
HCM: Hadamard coded modulation.
LACO-OFDM: layered ACO-OFDM
Li-Fi: light fidelity
MCM: multicarrier modulation
MM: metameric modulation
M-PAM: M-ary pulse amplitude modulation
M-PPM: M-ary pulse position modulation

OFDM: orthogonal frequency modulation
OOK: on-off keying
PAM-DMT: pulse amplitude modulation discrete multitone
PM-OFDM: position modulation OFDM
P-OFDM: polar OFDM
PWM: pulse width modulation
RPO-OFDM: reverse polarity optical OFDM
SCM: single carrier modulation
SEE-OFDM: spectrally and energy efficient OFDM
SFO-OFDM: spectrally factorized optical OFDM
WPDM: wavelet packet division multiplexing

▲Figure 1. Li-Fi modulation techniques considered in this paper.

pre-distortion techniques were proposed to mitigate non-linear distortion [4]. However, as the LED temperature increases the voltage-luminance (V-L) characteristic experiences memory-effects. Therefore, the LED non-linearity mitigation is still an open research problem. The limited bandwidth of Li-Fi communication channel leads to inter-symbol interference (ISI) at high data rates. The LED frequency response is modeled as a low-pass filter, and it is the major contributor to the frequency selectivity of Li-Fi channels. The modulation bandwidth over which the frequency response of most commercially available LEDs can be considered flat is around 2−20 MHz [5], [6]. However, the usable bandwidth in Li-Fi could be extended beyond the 3 dB cut-off frequency.

Therefore, modulation techniques with higher spectral efficiencies are key elements in a Li-Fi system design. Satisfying the illumination requirements is a key element in Li-Fi. Most of the research on modulation techniques has been on the communication system performance of Li-Fi system. Factors such as dimming, illumination level control and flickering have been analyzed as secondary parameters of a Li-Fi system. The Li-Fi systems should be also considered as an illumination system with communications capability, not the reverse.

3 Single Carrier Modulation Techniques

Single carrier modulation techniques were first proposed for IM/DD optical wireless communications based on infrared communications [7]. Modulation techniques, such as OOK, pulse amplitude modulation (PAM), pulse width modulation (PWM), and PPM, are straightforward to implement for Li-Fi systems. In general, single carrier modulation techniques are suitable candidates for Li-Fi when low-to-moderate data rates applications are required. By switching the LED between "on" and "off" states, the incoming bits can be modulated into the light intensity. Illumination control can be supported by adjusting the light intensities of the "on" and "off" states, without affecting the system performance. Compensation symbols are proposed in the visible light communications standard, IEEE 802.15.7 [8], to facilitate the illumination control at the expense of reducing the SE. If the link budget offers high signal to noise ratios (SNR), M-PAM can be used to modulate the incoming bits on the amplitude of the optical pulse [9].The position of the optical pulse is modulated into shorter duration chips in PPM with a position index that varies depending on the incoming bits. The PPM is more power efficient than OOK, however, it requires more bandwidth than OOK to support equivalent data rates. Differential PPM (DPPM) was proposed to achieve power and/or SE gains [10], however the effect of unequal bit duration for the different incoming symbols could affect the illumination performance. A solution was proposed in [11] to ensure that the duty cycle is similar among the different symbols to prevent any possible flickering. Variable PPM (VPPM) was proposed in the VLC standard IEEE 802.15.7 to

support dimming for the PPM technique and prevent any possible flickering. The pulse dimming in VPPM is controlled by the width of the pulse rather than the pulse amplitude. Therefore, VPPM can be considered as a combination of PPM and PWM techniques. Multiple PPM (MPPM) was proposed [12] as a solution to the dimming capability of PPM, where it was reported that it achieves higher spectral efficiencies than VPPM with less optical power dissipation. The advantages of PAM and PPM are combined in pulse amplitude and position modulation (PAPM) [13].

The performance comparison between single carrier and multicarrier modulation techniques was studied in [14]−[18] for different scenarios and considerations. The results may differ depending on the major considerations and assumptions of each study. However in general, the performance of single carrier modulation techniques deteriorate as the data rates increase, due to the increased ISI. Equalization techniques, such as optimum maximum likelihood sequence detection (MLSD), frequency domain equalizers (FDE), nonlinear decision feedback equalizers (DFE), and linear feed forward equalizer (FFE), are suitable candidates for equalization processes, with different degrees of performance and computational complexity [7], [19], [20]. The single carrier frequency domain equalizer (SC-FDE) was proposed for OWC as a solution to the high peak to average power ratio (PAPR) of OFDM in [12], [21]. PPM-SCFDE was considered in [22], and OOK-SCFDE was considered in [23]. The performance of OOK with minimum mean square error equalization (MMSE) was compared with the performance of asymmetrically clipped optical (ACO)-OFDM and the performance of complex modulation M-ary quadrature amplitude modulation (M-QAM) ACO-SCFDE in [18]. It was reported that the performance of ACO-SCFDE outperforms asymmetrically clipped optical OFDM (ACO-OFDM) and OOK-MMSE due to the high PAPR of ACO-OFDM when the nonlinear characteristics of the LED are considered. The performance of PAM-SCFDE is compared with OFDM in [12], without consideration of the LED nonlinearity. It was shown that PAM-SCFDE achieves higher performance gains when compared with OFDM at spectral efficiencies less than 3 bits/s/Hz.

Discrete Fourier transformation spread (DFT-s) OFDM was also considered for Li-Fi as a SCM that has the benefits of an OFDM multicarrier system with lower PAPR [24]. An extra pair of DFT and inverse discrete Fourier transformation (IDFT) operations are required to achieve DFT-s OFDM. Multiple independent streams of DFT-s OFDM modulated waveforms are separately transmitted through multiple LEDs in a single array. The performance of DFT-s OFDM is reported to be better when compared with DC-biased optical OFDM (DCO-OFDM) in terms of both PAPR and bit error rate (BER) [24]. A novel carrier-less amplitude and phase (CAP) modulation was proposed for Li-Fi in [25]. In order for CAP to suit the frequency response of LEDs, the spectrum of CAP was divided into m subcarriers by the aid of finite impulse response (FIR) filter. Al-

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though CAP is computationally complex, it could offer high spectral efficiencies in band-limited Li-Fi channel.

4 Optical OFDM

Single carrier modulation techniques require a complex equalization process when employed at high data rates. In addition, effects such as DC wandering and flickering interference of florescent lights may influence the system performance at the lower frequency regions of the used bandwidth. On the other hand, multicarrier modulation techniques such as OFDM can convert the frequency selective fading of the communication channel into a flat fading by employing the computationally efficient single tap equalizer. In addition, OFDM supports adaptive power and bit loading which can adapt the channel utilization to the frequency response of the channel. This can maximize the system performance. Supporting multiuser communication systems is an inherent advantage of OFDM, where each user could be allocated certain subcarriers. At the OFDM transmitter, the incoming bits are modulated into specific modulation formats such as M-QAM. The M-QAM symbols are loaded afterwards into orthogonal subcarriers with subcarrier spacing equal to multiple of the symbol duration. The parallel symbols can then be multiplexed into a serial time domain output, generally using inverse fast Fourier transformation (IFFT). The physical link of Li-Fi is achieved using off-the-shelf optoelectronic devices such as LED and photo-detectors (PD). Due to the fact that these light sources produce an incoherent light, the OFDM time-domain waveforms are used in Li-Fi to modulate the intensity of the LED source. Therefore, these waveforms are required to be both unipolar and real valued.

Hermitian symmetry is generally imposed on the OFDM input frame to enforce the OFDM time domain signal output into the real domain. Different variants of optical OFDM were proposed to achieve a unipolar OFDM output. DC bias is used in the widely deployed DCO-OFDM [26] to realize a unipolar time-domain OFDM output. However, OFDM signals have a high PAPR, which makes it practically impossible to convert all of the signal samples into unipolar ones. The OFDM time-domain waveform can be approximated with a Normal distribution when the length of the input frame is greater than 64. The DC bias point would be dependent on the V-L characteristic of the LED. Zero level clipping of the remaining negative samples after the biasing would result in a clipping distortion that could deteriorate the system performance. High DC bias would also incur some distortion as a result of the upper clipping of the OFDM waveform due to the V-L characteristic of the ideal LED. The forward-output current characteristic of an LED is shown in **Fig. 2**. Pre-distortion is used to linearize the dynamic range of the LED. The LED input and output probability distribution function (PDF) of the OFDM modulation signal are also shown. The dynamic range of the LED is between the turn-on bias and the maximum allowed current points of the LED. The
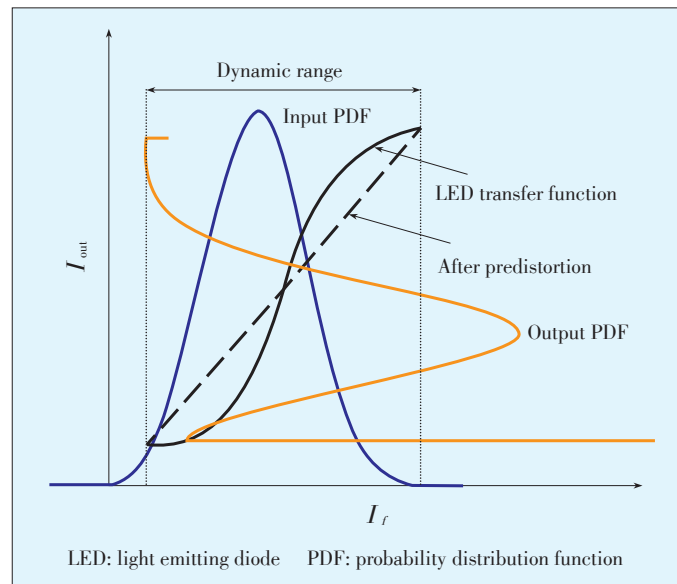
▲Figure 2. The forward-output current characteristic of an LED.

input signal is biased and the output signal is clipped for values outside the dynamic range. The optimization of the DC biasing point was studied in [27]−[29]. The additional dissipation of electrical power in DCO-OFDM compared with bipolar OFDM increases as the modulation order increases. This leads to electrical and optical power inefficiency when DCO-OFDM is used with high M-QAM modulation orders. Illumination is an essential part of VLC, therefore, the DCO-OFDM optical power inefficiency can be justified for some VLC applications. However, when energy efficiency is required, an alternative modulation approach is required.

4.1 Inherent Unipolar Optical OFDM Techniques

Unipolar OFDM modulation schemes were mainly introduced to provide energy efficient optical OFDM alternatives to DCO-OFDM. These schemes include ACO-OFDM [30], pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) [31], flipped OFDM (Flip-OFDM) [32], and unipolar orthogonal frequency division multiplexing (U-OFDM) [33]. They exploit the OFDM input/output frame structure to produce a unipolar time domain waveform output. However, all of these schemes have a reduced SE compared with DCO-OFDM due to the restrictions imposed on their frame structures. In this section, ACO-OFDM, PAM-DMT and U-OFDM/Flip-OFDM modulation schemes are discussed.

4.1.1 ACO-OFDM

A real unipolar OFDM waveform can be achieved by exploiting the Fourier transformation properties on the frequency domain input OFDM frames. The principle of ACO-OFDM [30] is to skip the even subcarriers of an OFDM frame, by only loading the odd subcarriers with useful information (**Fig. 3**). This creates a symmetry in the time domain OFDM signal, which al-

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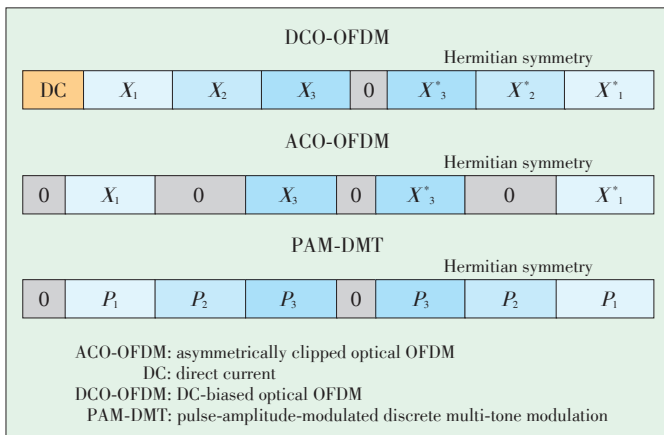
▲Figure 3. Subcarriers mapping of the input frames for DCO-OFDM, ACO-OFDM and PAM-DMT. X_i represents the M-QAM symbol at the ith subcarrier and P_i represents the M-PAM symbol at the ith subcarrier.

lows the distortion-less clipping of the negative samples without the need of any DC biasing (**Fig. 4**). Clipping of the negative values is distortion-less since all of the distortion will only affect the even-indexed subcarriers. However, skipping half of the subcarriers reduces the SE of ACO-OFDM to half of that in DCO-OFDM. A penalty of 3 dB should applied to the signal-to-noise ratio (SNR) of ACO-OFDM when compared with bipolar OFDM, since half of the signal power is lost due to clipping. Hermitian symmetry is also used to guarantee a real valued ACO-OFDM output. At the receiver, after a fast Fourier transformation (FFT) is applied on the incoming frame, only odd subcarriers are considered.

4.1.2 PAM-DMT

A real unipolar optical OFDM is realized in PAM-DMT by exploiting the Fourier properties of imaginary signals. The real component of the subcarriers is not used in PAM-DMT, which restricts the modulation scheme used to M-PAM (Fig. 3). By only loading M-PAM modulated symbols on the imaginary components of the subcarriers, an antisymmetry in the time-domain waveform of PAM-DMT would be achieved (**Fig. 5**). This would facilitate the distortion-less zero level clipping of PAM-DMT waveform, as all of the distortion would only affect the re-
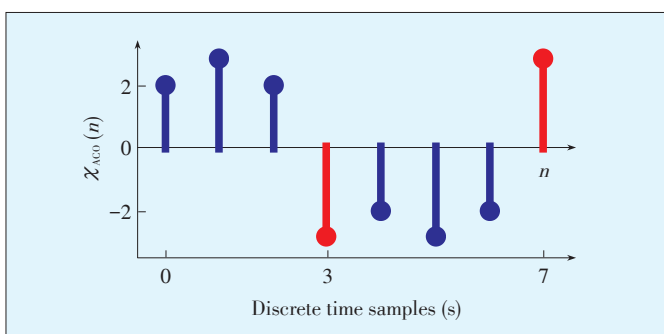
▲Figure 4. The time-domain ACO-OFDM waveform.
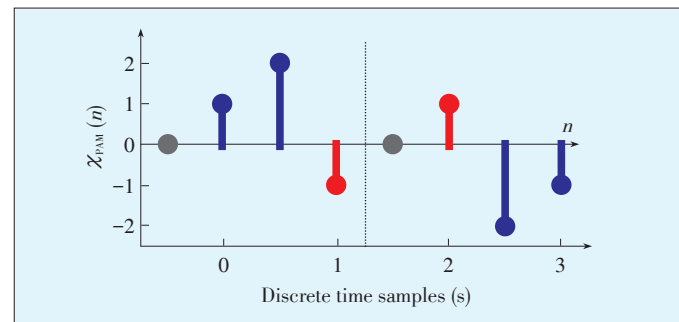
▲Figure 5. The time-domain PAM-DMT waveform.

al component of the subcarriers. Hermitian symmetry is also used to guarantee a real valued PAM-DMT output. PAM-DMT is more attractive than ACO-OFDM when bit loading techniques are considered, as the PAM-DMT performance can be optimally adapted to the frequency response of the channel since all of the subcarriers are used. The SE of PAM-DMT is similar to that of DCO-OFDM. PAM-DMT has a 3 dB fixed penalty when compared with bipolar OFDM at an appropriate constellation size, as half of the power is also lost due to clipping. At the receiver, the imaginary part of the subcarriers is only considered, while the real part is ignored.

4.1.3 U-OFDM/Flip-OFDM

The concept and performance of U-OFDM and Flip-OFDM is identical. In this paper, the term U-OFDM is used, however, all discussion and analysis is applicable to both schemes. Hermitian symmetry is applied on the incoming frame of M-QAM symbols. The bipolar OFDM time-domain frame obtained afterwards is expanded into two time-domain frames in U-OFDM with similar sizes to the original OFDM frame (**Fig. 6**). The first frame is identical to the original frame, while the second is a flipped replica of the original frame. A unipolar OFDM waveform can be achieved by zero-level clipping without the need of any DC biasing. At the receiver, each second frame would be subtracted from the first frame of the same pair, in order to reconstruct the original bipolar OFDM frame. This would double the noise at the receiver, which leads to a 3 dB penalty when compared with bipolar OFDM at equivalent constellation sizes. The SE of U-OFDM is half of the SE of DCO-OFDM since two U-OFDM frames are required to convey the same information conveyed in a single DCO-OFDM frame. The single tap equalizer can be used for U-OFDM, providing that the ISI effects on the first frame are identical to the ISI effects on the second frame.

4.1.4 Performance of Inherent Unipolar OFDM Techniques

The inherent unipolar OFDM schemes (ACO-OFDM, U-OFDM, and Flip-OFDM) were introduced as power efficient alternatives to DCO-OFDM. However because two time-domain U-OFDM/Flip-OFDM frames are required to convey the information contained in a single DCO-OFDM frame, and because

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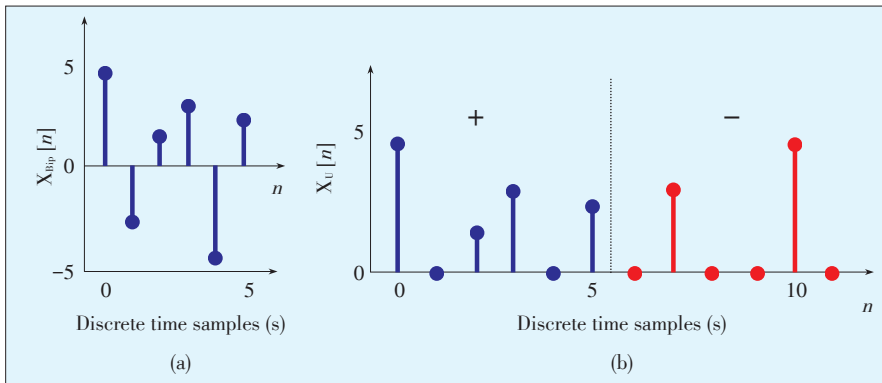
▲Figure 6. (a) Bipolar OFDM waveform; (b) U-OFDM waveform.

half of the subcarriers are skipped in ACO-OFDM, the performance of M-QAM DCO-OFDM should be compared with the performance of M^2-QAM (ACO-OFDM, U-OFDM, and Flip-OFDM). Additionally, PAM-DMT uses M-PAM on the imaginary part of the subcarriers instead of M-QAM. Since the performance of M-PAM is equivalent to the performance of M^2-QAM, the BER of PAM-DMT is similar to that of the inherent unipolar schemes. When compared with DCO-OFDM at the same SE, the performance of all of the inherent unipolar OFDM techniques degrades as the constellation size of M-QAM or M-PAM increases. For example, the performance of 1024-QAM ACO-OFDM/U-OFDM/Flip-OFDM and 32-PAM PAM-DMT would be required to be compared with the performance of 32-QAM DCO-OFDM.

Improved receivers for all of the inherent unipolar OFDM techniques were proposed in [33]−[41]. Most of these improved receivers would either require a flat channel to operate or incur additional computational complexities. Two main methods are considered in the design of these improved receivers. In the first method, the time-domain symmetry can be exploited at the receiver to achieve performance gains. An amplitude comparison between the symmetric received signal samples can improve the receiver detection in flat fading channels at the expense of increased computational complexity. The second method is based on the frequency diversity. The even subcarriers in ACO-OFDM and the real part of the subcarriers in PAM-DMT were exploited, respectively, to achieve improved performance at the receiver [33]−[41]. The frequency diversity method can be used in the frequency selective channel, however it has a higher computational complexity. In addition, it cannot be used for U-OFDM/Flip-OFDM because both schemes are based on the time-domain processing of the OFDM frames. Based on their statistical distribution, the inherent unipolar optical OFDM waveforms utilize the lower part of the V-L characteristic. Therefore, these schemes are suitable candidates for Li-Fi dimmable applications since they can operate with lower optical power dissipation. Adaptive bit loading techniques were studied for MCM techniques, DCO-OFDM and ACO-OFDM, and compared with SC-FDE in [42]. It was found that the performance of SC-FDE is worse than ACO-OFDM but better than DCO-OFDM. In addition, SC-FDE is less complex than DCO-OFDM and ACO-OFDM.

4.2 Hybrid OFDM Techniques

OFDM was modified in many studies to tailor several specific aspects of the Li-Fi system parameters. The natural spatial signal summing in the optical domain was proposed in [43]. An array of multiple LEDs is used to transmit the OFDM signal so that the subcarriers are allocated to different LEDs. As the number of the LEDs in the array increases, the PAPR of the electrical OFDM signals reduces. When the number of subcarriers is equal to the number of the LEDs in the array, the PAPR would reach its minimum value of 3 dB as the electrical signal would be an ideal sine wave. The spatial optical OFDM (SO-OFDM) is reported to have BER performance gains over DCO-OFDM at high SNR due to the reduced PAPR and the robustness against LED nonlinearities [43]. Reverse polarity optical OFDM (RPO-OFDM) was proposed to allow a higher degree of illumination control in the OFDM-based Li-Fi systems [44]. RPO-OFDM combines a real-valued optical OFDM broadband technique with slow PWM to allow dimming. The dynamic range of the LED is fully used in RPO-OFDM to minimize any nonlinear distortion. The RPO-OFDM is reported to achieve higher performance gains compared with DCO-OFDM at a large fraction of dimming ranges without limiting the data rate of the system. RPO-OFDM offers a practical solution for the illumination and dimming control for Li-Fi communication systems, however the OFDM signal in RPO-OFDM is based on unipolar OFDM. This means that the SE of RPO-OFDM is half of that of DCO-OFDM. As a result, the power efficiency advantage over DCO-OFDM starts to diminish as the SE increases. In addition, the PWM duty cycle is assumed to be known at the receiver, which means that side-information should be sent before any transmission and this requires perfect synchronization between the transmitting and receiving ends. A novel technique that combines ACO-OFDM on the odd subcarriers with DCO-OFDM on the even subcarriers was proposed in asymmetrically DC-biased optical OFDM (ADO-OFDM) [45]. The clipping noise of the ACO-OFDM falls only into the even subcarriers, and can be estimated and canceled with a 3 dB penalty at the receiver. The power allocation for different constellation sizes between ACO-OFDM and DCO-OFDM streams in ADO-OFDM was investigated in [15]. The optical power efficiency of the optimal settings for ADO-OFDM was better than ACO-OFDM and DCO-OFDM for different configurations. Hybrid asymmetrical clipped OFDM (HACO-OFDM) uses ACO-OFDM on the odd subcarriers and PAM-DMT on the even subcarriers to improve the SE of unipolar OFDM modulation techniques [46]. The asymmetrical clipping

of the ACO-OFDM on the odd symbols would only distort the even subcarriers. At the receiver, ACO-OFDM symbols are demodulated first by only considering the odd subcarriers and then remodulated to estimate the ACO-OFDM distortion on the even subcarriers. This allows the PAM-DMT symbols on the even subcarrier to be demodulated without any distortion. The SE achieved in HACO-OFDM is identical to that of DCO-OFDM, however PAM-DMT uses M-PAM modulation on half of the subcarriers. Equal power was allocated to ACO-OFDM and PAM-DMT. As the performance of M^2-QAM is equivalent to the performance of M-PAM, the power requirements for both ACO-OFDM and PAM-DMT to achieve the same performance is different. The problem also appears when different modulation orders are used for both schemes. Unequal power allocation for both schemes was investigated in [47] to guarantee that the performance of both schemes in HACO-OFDM is equal. An improved, but computationally complex, receiver was also proposed in [47] based on the time domain symmetry of both ACO-OFDM and PAM-DMT.

Polar OFDM (P-OFDM) is a new method to achieve the IM/DD for OFDM [48]. The main principle of P-OFDM is to convert the complex valued output of the IFFT from the Cartesian coordinates into the polar coordinates. Therefore, the radial and angular coordinate can be sent in the first and second halves of the OFDM frame, successively. It avoids the use of Hermitian symmetry, however, it allocates the M-QAM symbols into the even indexed subcarriers. As a result, P-OFDM has half-wave even symmetry which states that the first half of the complex valued time-domain frame is identical to the other half. Therefore, it is sufficient to transmit the first half of the IFFT output. As a result, the SE is reduced to be identical to that of DCO-OFDM since only half of the subcarriers are used. The performance of P-OFDM was compared to that of ACO-OFDM in [49]. It was reported that P-OFDM achieves better BER performance gains than ACO-OFDM under narrow dynamic ranges when optimal values for the power allocation of the radial and angular information are used. Note that any ISI between the radial and angular samples may deteriorate the system performance, therefore the system performance in frequency selective channels should be investigated. Asymmetrical and symmetrical clipping optical OFDM (ASCO-OFDM) was proposed in [50] for IM/DD Li-Fi systems. The ACO-OFDM is combined with symmetrical clipping optical OFDM (SCO-OFDM) that uses the even subcarriers. The clipping distortion of both ACO-OFDM and SCO-OFDM affects the even subcarriers. However, the clipping distortion of ACO-OFDM can be estimated and canceled at the receiver. The SCO-OFDM clipping noise can be removed at the receiver using U-OFDM/Flip-OFDM time domain processing techniques. The SE of ASCO-OFDM is 75% of the SE of DCO-OFDM. ASCO-OFDM was reported to have better symbol error rate (SER) compared with ADO-OFDM since the ADO-OFDM uses the DC bias for the even subcarriers. FIR filtering technique

termed spectral factorization was used to create a unipolar optical OFDM signal [51]. The amplitude of the subcarriers in spectral factorized optical OFDM (SFO-OFDM) were chosen to form an autocorrelation sequence that was shown to be sufficient to guarantee a unipolar OFDM output. The SFO-OFDM was reported to achieve 0.5 dB gain over ACO-OFDM with 30% PAPR reduction [51]. The position modulation OFDM (PM-OFDM) avoids the Hermitian symmetry and splits the real and imaginary components of the OFDM output into two branches where a polarity separator is used to obtain the positive and negative samples of each branch [52]. The four frames composed of a real positive frame, a real negative one, an imaginary positive one and an imaginary negative one are transmitted as unipolar OFDM frames. The SE is exactly similar to other inherent unipolar OFDM techniques discussed in section 4.1. The performance of PM-OFDM was reported to be identical to U-OFDM in flat channels. However, it was reported to have better BER performance when compared to ACO-OFDM for frequency selective channels [52].

4.3 Superposition OFDM Techniques

Superposition OFDM based modulation techniques rely on the fact that the SE of U-OFDM/Flip-OFDM, ACO-OFDM, and PAM-DMT can be doubled by proper superimposing of multiple layers of OFDM waveforms. Superposition modulation was first introduced for OFDM-based OWC and has led to enhanced U-OFDM (eU-OFDM) [53]. The eU-OFDM compensates for the spectral efficiency loss of U-OFDM by superimposing multiple U-OFDM streams so that the inter-stream-interference is null. The generation method of the first depth in eU-OFDM is exactly similar to that in U-OFDM. Subsequent depths can be generated by U-OFDM modulators before each unipolar OFDM frame is repeated 2^{d-1} times and scaled by $1/2^{d-1}$, where d is the depth number. At the receiver, the information conveyed in the first depth is demodulated and then remodulated to be subtracted from the overall received signal. Then repeated frames which are equivalent at higher depths are recombined and the demodulation procedure continues the same as for the stream at the first depth. Afterwards, the information conveyed in latter depths is demodulated in a similar way. The SE gap between U-OFDM and DCO-OFDM can never be completely closed with eU-OFDM, as this would require a large number of information streams to be superimposed in the modulation signal. Implementation issues, such as latency, computational complexity, power penalty, and memory requirements put a practical limit on the maximum number of available depths. The eU-OFDM was generalized in the Generalized Enhanced Unipolar OFDM (GREENER-OFDM) for configurations where arbitrary constellation sizes and arbitrary power allocations are used [54]. As a result, the SE gap between U-OFDM and DCO-OFDM can be closed completely with an appropriate selection of the constellation sizes in different information streams. The symmetry in U-OFDM lies in frames,

whilst in ACO-OFDM and PAM-DMT, it lies in subframes.

The superposition concept has also been extended to other unipolar OFDM techniques such as PAM-DMT [55] and ACO-OFDM [56]–[60]. The enhanced asymmetrically clipped optical OFDM (eACO-OFDM) [56] uses the symmetry of ACO-OFDM subframes to allow multiple ACO-OFDM streams to be superimposed. A similar concept was also proposed by Elgala et al. and Wang et al. under the names of spectrally and energy efficient OFDM (SEE-OFDM) [57] and layered asymmetrically clipped optical OFDM (Layered ACO-OFDM) [58], respectively. The receiver proposed in SEE-OFDM [57] results in SNR penalty that could have been avoided by using the symmetry properties of ACO-OFDM streams. The symmetry arrangement in Layered ACO-OFDM [58] is described in the frequency domain, however, it is shown in [58, Fig.2] that it takes place in the time-domain. Recently, an alternative method to achieve superposition modulation based on ACO-OFDM was proposed by Kozu et al. [59] for two ACO-OFDM streams, and Lawery [60] for Layered ACO-OFDM. This is similar in principle to the solutions in [56]–[58], however the superposition is performed in the frequency domain which results in simpler system design. The concept of eACO-OFDM was generalized to close the SE gap between ACO-OFDM and DCO-OFDM. The generation of eACO-OFDM signal starts at the first depth with an ACO-OFDM modulator. Additional depths are generated in a similar way to the first depth, but with an OFDM frame length equal to half of the previous depth frames. Similar to eU-OFDM, all of the generated frames are repeated 2^{d-1} times and appropriately scaled. The demodulation process at the receiver is applied in a similar way as the eU-OFDM. The information at Depth-1 can be recovered directly as in conventional ACO-OFDM because all of the inter-stream-interference falls into the even-indexed subcarriers. After the first stream is decoded, the information can be remodulated again and subtracted from the overall received signal. Then, the frames that are equivalent can be recombined and the demodulation procedure continues as for the stream at first depth.

The enhanced pulse-amplitude-modulated discrete multi-tone (ePAM-DMT) [55] demonstrates that superposition modulation can also be utilized when the antisymmetry of PAM-DMT waveforms is used. Analogous to eU-OFDM and eACO-OFDM, unique time-domain structures are also present in PAM-DMT. If the interference over a single PAM-DMT frame possesses a Hermitian symmetry in the time-domain, its frequency profile falls on the real component of the subcarriers. Hence, the interference is completely orthogonal to the useful information which is encoded in imaginary symbols of the PAM-DMT frames. The concept of superposition modulation was extended to ePAM-DMT for an arbitrary modulation order and an arbitrary power allocation at each depth [55]. The theoretical BER analysis of eACO-OFDM is similar to the analysis of GREENER-OFDM, therefore the optimal modulation sizes and scaling factors are identical. This is an expected result because the

performance of their unipolar OFDM forms, ACO-OFDM and U-OFDM, is also similar. The ePAM-DMT is less energy efficient than GREENER-OFDM and eACO-OFDM, because ePAM-DMT has 3 dB loss in each depth demodulation process and the optimal configurations of ePAM-DMT are suboptimal as the non-squared M-QAM BER performance can never be achieved using the $\sqrt{M}$-PAM modulation scheme. The ePAM-DMT is more energy efficient than DCO-OFDM in terms of the electrical SNR at SE values above 1 bit/s/Hz. In terms of the optical SNR, the ePAM-DMT is less energy efficient than DCO-OFDM for all of the presented values. Higher optical energy dissipation is a desirable property for illumination based Li-Fi applications, but it is considered as a disadvantage for dimmable-based Li-Fi applications. However, GREENER-OFDM and eACO-OFDM are suitable candidates for dimmable-based Li-Fi applications due to their optical SNR performance.
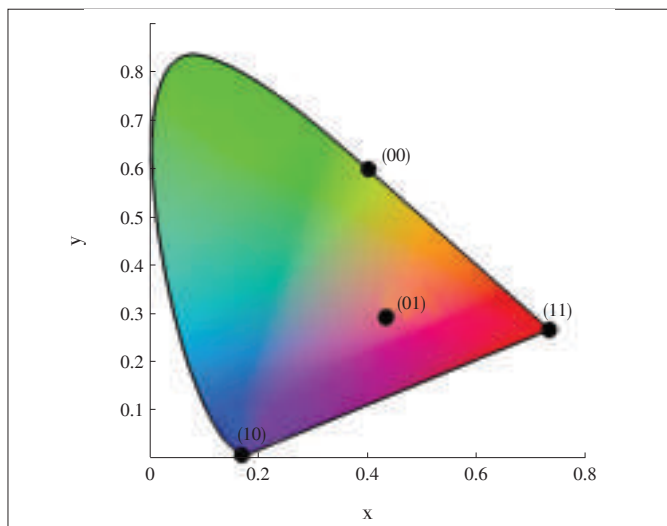
5 Other Multi-Carrier Modulation Techniques

OFDM has been mainly studied in the context of Li-Fi channels based on FFT. Other transformations such as discrete Hartley transformation (DHT) [61], wavelet packet division multiplexing (WPDM) [62] and Hadamard coded modulation (HCM) [63] have also been considered for Li-Fi channels. A multicarrier IM/DD system based on DHT was proposed in [61]. It was shown that DHT output can be real when an input frame of real modulated symbols such as binary phase shift keying (BPSK) and M-PAM is used. Similar to DCO-OFDM and ACO-OFDM, DC-biasing and asymmetrical clipping can also be used to achieve unipolar output in DHT-based multi-carrier modulation technique. As a major advantage over FFT-based conventional OFDM, the DHT-based multicarrier modulation does not require any Hermitian symmetry. However, this fails to improve the SE as real modulated symbols such as M-PAM are used in DHT-based multicarrier modulation. WPDM uses orthogonal wavelet packet functions for symbol modulation where the basis functions are wavelet packet functions with finite length. It was reported that the performance of WPDM is better than that of OFDM in terms of the spectral and power efficiencies when LED nonlinear distortion and channel dispersion are taken into account [62]. The high illumination level of OFDM Li-Fi systems require higher optical power, which may result in clipping due to the peak power constraint of the V-L transfer function of the LED (Fig. 2). HCM was proposed for multicarrier modulation Li-Fi as a solution to the limitation of OFDM modulation at higher illumination levels. The technique is based on fast Walsh-Hadamard transformation (FWHT) as an alternative to the FFT. HCM is reported to achieve higher performance gains when compared with ACO-OFDM and DCO-OFDM at higher illumination levels [63]. However, the performance improvement over RPO-OFDM is modest. An alternative variant of HCM, termed DC reduced

HCM (DCR-HCM), was also proposed to reduce the power consumption of HCM to support dimmable Li-Fi applications, and interleaving with MMSE equalization is used for HCM in dispersive Li-Fi channels.

6 Li-Fi Unique Modulation Technique

The modulation frequency in Li-Fi systems does not correspond to the carrier frequency of the LED. All the aforementioned modulation techniques are baseband modulation techniques. It is practically difficult to modulate the carrier frequency of the LEDs, however, it is practically straightforward to change its colour. This feature adds a new degree of freedom to Li-Fi systems. Colour tunable LEDs such as the red green blue LED (RGB-LED) can illuminate with different colours based on the intensity applied on each LED element. The IEEE 802.15.7 standard proposes colour shift keying (CSK) as a modulation technique for VLC [8]. The incoming bits are mapped into a constellation of colours from the chromatic CIE 1931 colour space [64], as shown in **Fig. 7**. The CIE 1931 is the widely used illumination model for human eye colour perception. Any colour in the model can be represented by the chromaticity dimension $[x, y]$. In CSK, the overall intensity of the output colour is constant, however, the relative intensities between the multiple used colours are changed. Therefore the instantaneous colour of the multicolour LED is modulated. Seven wavelengths are defined in IEEE 802.15.7 specify the vertices of a triangle where the constellation point lies in. The intensity of each RGB-LED element is changed to match the constellation point while maintaining a constant optical power and a constant illumination colour. This is desirable in Li-Fi systems, since the constant illumination colour naturally mitigates any flickering. An amplitude dimming is used for brightness control in CSK while the center colour of the colour constella-

tion constant is kept. However, colour shift is possible due to the presence of any improper driving current used for dimming control. Constellation sizes up to 16-CSK were proposed in the IEEE 802.15.7 standard based on tri-colour LEDs. Constellation points design based on CIE 1931 was also investigated by Drost and Sadler using billiard algorithms [65], by Monterio and Hranilovic using interior point method [66], by Singh et al. using quad LED (QLED) [67], and by Jiang et al. using extrinsic transfer (EXIT) charts for an iterative CSK transceiver design [68].

A generalized CSK (GCSK) that operates under varying target colours independent from the number of used LEDs was proposed in [69]. Colour intensity modulation (CIM) was proposed to improve the communication capacity without any loss to the illumination properties (dimming and target colour matching) [70]. The instantaneous intensity of the RGB LED was modulated in CIM while only maintaining a constant perceived colour. Therefore, CIM can be considered as a relaxed version of CSK since a constant perceived power is additionally required in CSK. Metameric modulation (MM) constrains the CSK to have a constant instantaneous perceived ambient light with the aid of an external green LED [70]. An improved control of the RGB output colour was achieved in MM by improving the colour rendering and reducing the colour flickering [71]. A four colour system was used in [67] with the aid of additional IM/DD signaling as a fourth dimension signal. Higher order modulation techniques of 2^{12}-CSK for QLED were achieved in [67]. The CSK was combined with constant rate differential PPM in [72] to simplify the synchronization while maintaining the illumination control and avoiding flickering. A similar approach of combining CSK with complementary PPM was proposed by [73]. A digital CSK (DCSK) was proposed in [74]. Multiple multicolour LEDs were used in DCSK where only one colour is activated in each multicolour LED at a single time. Therefore the information is encoded in the combinations of activated colours. The main advantage of DCSK over conventional CSK is avoiding the need of any digital-to-analog converters, while the main disadvantage is rendering the activated colours which may result in slight changes of the colour perception over time.

The receiver architecture has not been fully addressed in most of the published research on colour domain modulation. CSK is considered to be an expensive and complex modulation technique when compared with OFDM. The colour dimension in Li-Fi can also be used to derive a multicolour LED with different streams of data. The optical summation may turn this coloured parallel stream into a single colour stream output that can be filtered at the receiver into the original transmitted coloured stream.

▲Figure 7. The symbol mapping of 4-CSK on the CIE 1931 colour model based on IEEE 802.15.7.

7 Conclusions

The modulation techniques suitable for Li-Fi are presented

in this paper. These techniques should satisfy illumination and communication requirements. Single carrier modulation techniques offer a simple solution for frequency-flat Li-Fi channels. Low-to-medium data rates can be achieved using single carrier modulation techniques. Multicarrier modulation techniques offer high data rates solution that can adapt the system performance to the channel frequency response. Many variants of optical OFDM modulation techniques have been proposed in published research to satisfy certain illumination and/or communication requirements. A summary of Li-Fi multicarrier modulation techniques is presented in **Table 1**. The colour di-

▼Table 1. Comparison of multicarrier modulation schemes for Li-Fi

Mod. Tech.	SE as a function of DCO-OFDM	Illumination		Computational complexity	Remarks	Ref.
		Control	Level			
ADO-OFDM	100%	No	Dimmed-medium	High	Requires DC bias	[15]
DCO-OFDM	100%	No	Medium	Low	Requires DC bias	[26]
Inherent unipolar	50%	No	Dimmed	Low	Power efficient at low SE	[30]–[33]
Spatial OFDM	100%	Limited	Medium	High	Low PAPR	[43]
RPO-OFDM	50%	Yes	Dimmed-high	Medium	Requires sync.	[44]
HACO-OFDM	100%	No	Dimmed	High	Power efficient at low-medium SE	[46]
P-OFDM	50%	No	Medium	High	-	[48]
ASCO-OFDM	75%	No	Dimmed	High	-	[50]
SFO-OFDM	Variable	No	Medium	High	Low PAPR	[51]
PM-OFDM	50%	No	Medium	High	-	[52]
Superposition	100%	No	Dimmed	High	Power efficient at low-high SE	[53]–[60]
DHT	50%-100%	No	Dimmed-medium	Low	-	[61]
WPDM	100%	No	Medium	High	-	[62]
HCM	100%	Yes	High	Low	Power inefficient	[63]

mension offers unique modulation formats for Li-Fi and adds to the degrees of freedom of Li-Fi systems. Time, frequency, space, colour dimensions, and the combinations of them can be used for Li-Fi modulation. Li-Fi modulation techniques should offer a high speed communication and be suitable for most illumination regimes.

Acknowledgment

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