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Analyzing the impact of nonlinear distortions on OFDM-Based visible light communication systems

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ABSTRACT

Visible light communication (VLC) has gained attraction for its use in high-speed wireless connectivity leveraging LED lighting elements. Orthogonal Frequency Division Multiplexing (OFDM) is an attractive modulation scheme due to its spectral efficiency and resilience to multipath distortion. However, the nonlinear electro-optic transfer characteristics of optical components introduce signal clipping and quantization noise which corrupt OFDM signals. This paper provides an in-depth analysis of clipping and quantization noise to quantify the impact of LED nonlinearities on OFDM-based VLC system performance. Detailed mathematical models are derived for clipping distortions caused by LED optical power saturation and quantization errors from ADC/DAC finite precision in the modulator and driver circuitry. This analysis is quantified through simulations of the degradations in terms of error vector magnitude (EVM), signal-to-noise ratio (SNR) loss, and bit error rate (BER) under varying clipping ratios and quantization bit-depths. The 16-QAM OFDM transmission shows that the LED driver should possess at least 12 dB signal linear dynamic range and 3-bit quantization to restrict SNR penalty within 3 dB. Adaptive tone mapping and digital pre-distortion techniques are examined to compensate for intensity distortions enabling high-speed OFDM transmission over VLC links.

1. Introduction

Light-emitting diodes (LEDs) have emerged as an efficient lighting technology and are rapidly replacing conventional lights for next-generation smart lighting systems. Visible light communication (VLC) leverages such LED luminaries to provide both illumination and high-speed wireless connectivity without requiring additional infrastructure[1]. This has driven recent research into suitable modulation schemes for supporting emerging bandwidth-hungry applications over VLC links [2]. VLC is a promising technology for high-speed indoor wireless access, offering advantages such as globally unlicensed bandwidth, high signal-to-noise ratio (SNR), and low-cost intensity modulation direct detection (IM/DD) architecture. Data are integrated at the light-emitting diode (LED) of the transmitter and detected by photodetectors (PD) at the receiver due to the high spectral efficiency of optical orthogonal frequency division multiplexing (O-OFDM). and the difference from the optical diffuse channel (VLC) has played a major role in systems due to its resistance to symbol interference (ISI).

The O-OFDM is characterized by a high peak-to-average power ratio (PAPR), which makes LEDs weakly nonlinear, which leads to many nonlinear distortions, which must be reduced to improve the message[3]. The effect of LED nonlinearity on message quality requires mitigation solutions, such as amplitude clipping and filtering, selective mapping (SLM), partial transmission sequence (PTS), tone reservation and injection, discrete Fourier transform spread, and other monolithic matrices, the PAPR-reduction scheme (DFT-S), and Hadamard precoding with modifications. These techniques aim to reduce PAPR without causing any signal distortion or noise. In addition, adaptive tone mapping and digital pre-distortion have been proposed as methods to compensate for nonlinear distortions in O-FDM-VLC systems[4]. As VLC technology becomes increasingly popular over radio frequency communication, it is important to investigate the effect of nonlinear distortions in O-FDM-VLC systems The successful implementation of VLC will depend on finding effective solutions to reduce these distortions [5].

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Nomenclature:

Δf	Frequency Spacing Between OFDM Subcarriers (Hz).
Δ	DAC/ADC quantum step size.
Ts	OFDM Symbol Duration(s).
$X[k]$	Frequency Domain Complex Data Symbols.
$x(t)$	Time-Domain OFDM Signal.
N	Number Of OFDM Subcarriers.
k	Subcarrier Index.
TCP	Cyclic Prefix Length (Time Duration) (s).
$H(0)$	DC Channel Gain.
d	Transmitter-Receiver Separation Distance(m).
A	Photodetector Area(m^2).
m	Lambertian Emission Order.
$Po(t)$	Optical Power(w).
$ID(t)$	LED Drive Current(A).
$i(t)$	Message Signal Current(A).
IDC	DC Bias Current(A)
$IMAX$	Maximum LED Current(A).
$AMAX$	Half of Peak Drive Current(A).
$nCLIP(t)$	Clipping Distortion Noise.
$P(clip)$	Clipping Probability.
C	Clipping Threshold.

Greek symbols

φ	Angle Of Irradiance (deg.).
ψ	Angle Of Incidence (deg.).
$Tp(\psi)$	Optical Filter Gain.
$g(\psi)$	Concentrator Gain.
ηQE	Photon Conversion Efficiency.
$\hat{\imath}(t)$	Clipped LED Waveform(A).
μ	OFDM signal.
σ	OFDM variance
$\sigma x2$	Variance of message signal.

Orthogonal frequency division multiplexing (OFDM), relying on multiple narrowband lower-rate subcarrier transmissions in parallel, has been widely adopted for RF wireless systems owing to its high bandwidth efficiency, ease of equalization, and resilience to inter-symbol interference caused by frequency-selective optical wireless channels [6]. The combination of OFDM signaling and dense spectral reuse makes it an attractive solution to meet the ever-growing data bandwidth demands for indoor VLC systems. However, intensity modulation/direct detection (IM/DD)-based optical wireless imposes certain restrictions, including nonnegative real-valued signaling and nonlinear optoelectronic conversion processes [7]. The LED exhibits a nonlinear electro-optic transfer characteristic that, when subjected to the high peak-to-average power ratio (PAPR) OFDM signals, generates nonlinear distortion noise, causing significant corruption, Prior works have analyzed the impact of clipping or saturation-type distortions owing to LED nonlinearity on OFDM error performance [8]. However, a unified analysis looking at the different nonlinear noise sources from optical and electrical driver components is still lacking.

Mitigation of nonlinear distortions is pivotal for OFDM VLC. Advanced evaluation using unique statistical fashions and mathematical tradeoff studies will quantify predicted distortions and potential limits. The proposed enhancements outlined will bolster technical rigor [9]. In this paper, we provide an in-depth analysis of the various intensity distortion mechanisms in LEDs and drivers that degrade OFDM signaling over VLC links. The key research contributions are:

- Presenting detailed mathematical models for clipping distortions owing to LED optical power saturation and quantization errors from ADC/DAC finite bit-precision in the transceiver circuitry.
- Quantifying through simulations the impact of nonlinear distortions on the performance of IM/DD OFDM-based VLC systems in terms of error vector magnitude (EVM), (SNR) ratio degradations, and bit error rate (BER).
- Providing design guidelines on LED linearity requirements including IP3, signal dynamic range for target OFDM transmission data rates, and modulation formats.
- Discussing pre-distortion-based amplitude and tone mapping along with post-equalization techniques to mitigate intensity distortions induced by LED nonlinearities.

The remainder of this paper is structured as follows. Section 2. Literature Review. Section 3. describes a typical white-LED OFDM VLC architecture and presents background on OFDM signaling. Section 4. details the LED distortion characteristics and Nonlinear Distortions in OFDM-VLC. Section 5. Mathematical Models for Nonlinear Distortions. Section 5. Impact of Nonlinear Distortions on OFDM-VLC. Section 7. Techniques for Compensating Nonlinear Distortions. Section 8. Analyzes the simulations and performance impact under varying distortion levels. Section 9. Result and Finally, Section 10. provides the concluding remarks and future research directions. The Methods have been proposed to enhance data rates under limited LED dynamic range. Pre-distortion using polynomial curve fitting and memoryless normalization techniques have demonstrated improvements in linearizing electro-optic transfer characteristics. However, most literature focuses on single distortion analysis lacking clip-level dependent performance evaluations. There also remains scope for comparing the merits of electrical and optical domain compensation techniques. A unified mathematical framework benchmarking the end-to-end impact of different linear and nonlinear distortions will aid OFDM system design decisions.

2. Literature review

X. Li et al.[10] The paper provides a comprehensive analysis of the various modulation techniques employed in visible light communication (VLC) systems. As a rapidly emerging technology, VLC has attracted significant interest from researchers due to its potential to offer higher data rates, improved energy efficiency, and secure communication compared to conventional wireless technologies such as Wi-Fi and LTE. The authors begin by highlighting the fundamental requirements of VLC systems, emphasizing the need for dimming support to adjust light intensity levels based on application needs and flicker mitigation to prevent adverse physiological effects on humans caused by fluctuations in light intensity. These factors play a crucial role in the selection and design of appropriate modulation schemes for VLC systems. The paper delves into a detailed discussion of different modulation techniques, categorized into single-carrier and multi-carrier schemes. Among the single-carrier schemes, the authors explore On-Off Keying (OOK), Pulse Modulation methods (including Pulse Width Modulation, Pulse Position Modulation, and their variants), and Color Shift Keying (CSK). The authors provide an in-depth analysis of the advantages, limitations, and performance metrics (such as data rate, signal-to-noise ratio, and bit error rate) associated with each modulation scheme. For multi-carrier modulation, the paper focuses on Orthogonal Frequency Division Multiplexing (OFDM), which effectively mitigates intersymbol interference and multipath fading. The authors discuss the challenges of implementing OFDM in VLC systems, such as the need for real-valued unipolar signals and the non-linearity of LEDs, which can lead to clipping distortion and limited dimming support.

One of the strengths of this paper lies in its comprehensive comparative analysis of the reviewed modulation schemes. The authors consider critical parameters such as dimming factor, power requirements, spectral efficiency, and data rate, providing valuable insights into the trade-offs and potential applications of each scheme. This analysis serves as a valuable resource for researchers and engineers working on the development and optimization of VLC systems. Overall, the paper "A Review of Modulation Schemes for Visible Light Communication" serves as an excellent reference for understanding the state-of-the-art modulation techniques in VLC and their implications on system performance, dimming support, and flicker mitigation. The authors' meticulous review and comparative analysis contribute significantly to the existing literature and can guide future research and development efforts in this rapidly evolving field of visible light communication.

S. Rajbhandari et al. [11] the Paper proposed the Intensity-modulation direct-detection constraints necessitate real and positive signaling in visible light optical wireless communication systems. This makes orthogonal frequency division multiplexing with its high peak-to-average power ratio distribution susceptible to nonlinear distortions from LED and driver elements. Prior works have developed analytical models for LED clipping noise and quantization errors to estimate error-vector magnitude and signal-to-noise ratio degradations. Bit-loading optimization and dynamic bias control methods have been proposed to enhance data rates under limited LED dynamic range. Pre-distortion using polynomial curve fitting and memoryless normalization techniques have demonstrated improvements in linearizing electro-optic transfer characteristics. However, most literature focuses on single distortion analysis lacking clip-level dependent performance evaluations. There also remains scope for comparing the merits of electrical and optical domain compensation techniques. A unified mathematical framework benchmarking the end-to-end impact of different linear and nonlinear distortions will aid OFDM system design decisions.

C. He et al. [12]. This research paper presents a rigorous examination of the nonlinearity effects induced by light-emitting diodes (LEDs) on orthogonal frequency division multiplexing (OFDM) optical wireless transmission systems. The authors have meticulously developed a simulation model that accurately replicates the nonlinear transfer characteristics of a high-power infrared LED. This model enables an in-depth analysis of how the selection of the bias point and power back-off strategies impact critical system performance indicators, such as the bit-error-rate (BER) and the error vector magnitude (EVM). Optical OFDM shows promise for next-gen optical wi-fi conversation, however generating real, fine alerts gives problems. Proposed unipolar OFDM strategies like ACO-OFDM and DCO-OFDM still showcase problematic clipping distortion. Mitigation strategies extensively encompass optimization of ACO/DCO parameters, decision-directed reconstruction (DDSR), and gadget learning-aided recuperation. Analyses have characterized clipping noise residences to optimize parameters for each single and double-sided clipping, deriving metrics such as variance, shrinkage ratio, optical power, and image error costs. However, the impacts of decision mistakes on reconstructed indicators require a similar inquiry. While progress has been finished, most works do not optimize DDSR thresholds for practical noise conditions. Additionally, decision error results warrant deeper evaluation. Further exploration into device mastering for optical OFDM signal healing provides open studies capability. Developing computationally green solutions strong to numerous noise environments is an ongoing project.

3. OFDM signaling for VLC systems

3.1 Background on OFDM and VLC

VLC, or visible light communication, is a developing wireless technology that uses LED lights to transmit data optically. VLC offers several merits, including immunity to RF interference, reduced power consumption, enhanced security, and high data rate capabilities. The widely adopted Orthogonal Frequency Division Multiplexing (OFDM) technique is the modulation scheme of choice for VLC systems due to its spectral efficiency, simple channel equalization implementation, and low computational complexity. The broadly accompanied orthogonal frequency division multiplexing (OFDM) method in VLC structures is chosen for its immoderate spectral performance, easy equalization, and espresso complexity implementation. However, the presence of nonlinear additives inside the VLC device motives distortion to the OFDM signal, crucial to overall performance degradation. This distortion is often because of the nonlinearity within the electro-optic transfer feature of the transmitting LED because the signals are intensity-modulated onto the optical power[13]. The nonlinear switch capabilities of LEDs bring about reduced transmission general overall performance in OFDM-based completely VLC structures due to the excessive height-to-average energy ratio (PAPR) of the time-area signal. Additionally, limitations on pinnacle transmitted energy and nonnegative transmitted signal constraints from lighting resources can cause nonlinear signal distortion from clipping. To deal with those issues, several OFDM modulation schemes have been superior, which consist of Direct Current OFDM (DCO-OFDM) and Asymmetrically Clipped OFDM (ACO-OFDM). These schemes' purpose is to make certain that the transmitted signal is actual and non-poor at the same time minimizing clipping distortion due to LED nonlinearity[14]. Aside from LED nonlinearity, unique optical front-give-up components like analog-to-digital converters, virtual-to-analog converters, LEDs, and photodiodes moreover make contributions to nonlinear distortion in VLC structures. As shown in fig (1). The limited range of the front-give-up VLC systems is due to the saturation effects of LEDs and p-n junction borders, resulting in limitations on bandwidth and peak transmitted power[15]. To deal with LED nonlinear distortion, pre-distortion, and positioned up-distortion strategies may be employed. Adaptive tone mapping and virtual pre-distortion are mainly designed to capture nonlinear distortions because of LED tendencies. In forestall, understanding, and mitigating nonlinear distortions is critical for optimizing commonplace overall performance in OFDM-based seen slight verbal exchange structures[16].

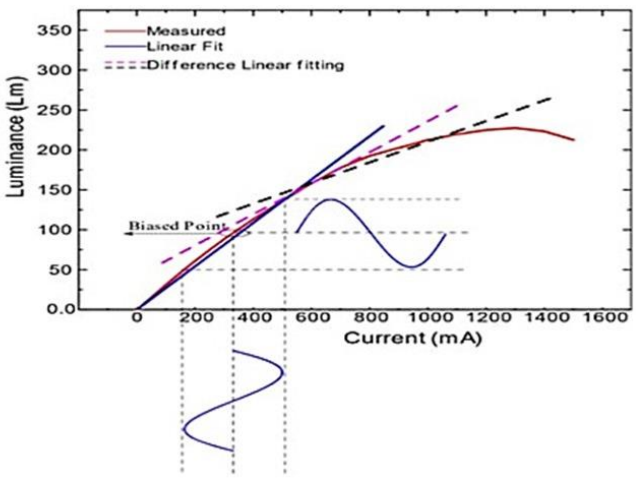

Figure 1. Nonlinear LED transfer function [16]

3.2 Conventional IM/DD VLC architecture

Figure 2 shows a typical indoor LOS (line-of-sight) intensity modulation direct detection (IM/DD), VLC system with an LED transmitter, and photodetector (PD) receiver [17]. The input binary data drives an OFDM modulator to generate complex time-domain symbols which are used to intensity modulate the LED element. The visible light output is focused and channeled through the LOS link which due to the absence of light interference from artificial sources can be modeled by (LOS) channel impulse response. The PD collects the optical power which is proportional to the instantaneous intensity waveform and transformed into an electrical current signal. A trans-impedance amplifier (TIA) along with analog signal conditioning provides the necessary gain and bandwidth rectification before analog-to-digital conversion. The digitized samples feed the DSP-based OFDM demodulator for data recovery.

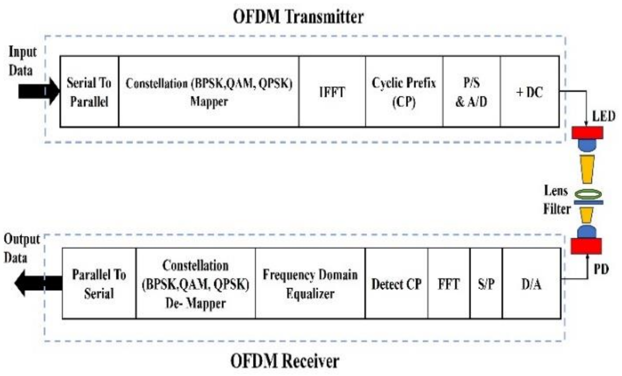

Figure 2. IM/DD OFDM-based VLC System Architecture.

3.3 Overview of OFDM signaling

We consider an OFDM system with N subcarriers with frequency spacing Δf = 1/Ts, where Ts denotes the OFDM symbol duration. Let X[k] be the frequency domain complex data symbols which are modulated onto sub-carriers using M-ary quadrature amplitude modulation (M-QAM) or phase shift keying (M-PSK). The corresponding time-domain signal x(t) is obtained by taking the N-point inverse discrete Fourier transform (IDFT) given by:

$$\boldsymbol{x(t)} = \frac{\mathbf{1}}{\sqrt{\boldsymbol{N}}} \sum \boldsymbol{x(k)} \boldsymbol{e^{2j\pi k \Delta f t}} \qquad (\mathbf{0} \le \boldsymbol{t} \le \boldsymbol{T_s}) \tag{1}$$

To avoid inter-block interference (IBI) from channel multipath dispersion, a cyclic prefix (CP) of length TCP is inserted before to transmission as shown in Fig. (3). After D/A conversion and driver amplification, the real-valued bipolar signal modulates the LED intensity. At the receiver, the reverse operations of OFDM demodulation are performed to recover the original data symbols[18] .

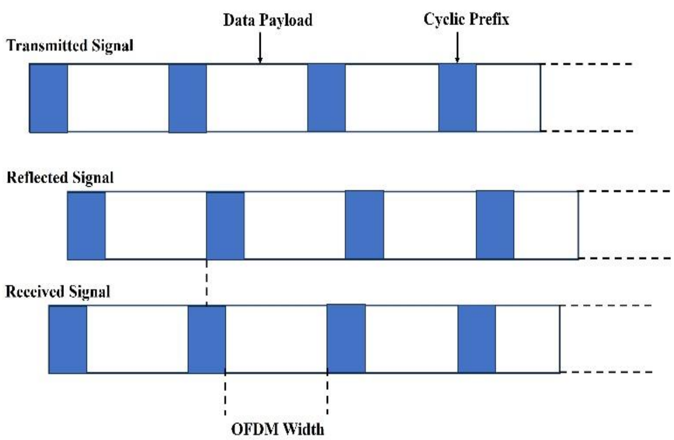

Figure 3. OFDM signalling structure with cyclic prefix [18].

OFDM provides resilience to multipath-induced ISI since the symbol rate is lowered by parallel subcarrier transmission. Also, simple frequency domain equalization can invert channel distortion on individual sub-carriers. However, the time-domain OFDM signal composed of the sum of sinusoids exhibits a peaky distribution with a high peak-to-average power ratio. This makes it susceptible to nonlinear distortions [19].

3.4 VLC channel characteristics

The visible light communication (VLC) channel exhibits unique propagation properties compared to traditional radio frequency (RF) wireless media since the signal transmission occurs through modulation of optical intensity in the visible light spectrum. The channel model hence needs to capture optical path loss, line-of-sight (LOS) shadowing, as well as multipath distortions from reflections, enabling reliable system analysis and design [20]. The DC channel gain over a LOS link can be represented as:

$$H(0) = \left(\frac{A}{d^2}\right) \times cos^m(\varphi) \times T_p(\psi) \times g(\psi) \times \cos(\psi) \tag{2}$$

Where *d* denotes the transmitter-receiver separation distance, *A* the physical area of the photodetector (PD), φ is the angle of irradiance concerning the transmitter axis and ψ represents the angle of incidence concerning the PD axis. Term *Tp(ψ)* denotes the gain of the optical filter used while *g(ψ)* is the concentrator gain factor. The order m depends on the Lambertian emission profile. In addition to path loss that increases with higher-order emission modes, shadowing causes momentary obstruction of LOS light when objects intersect the visibility region. The impulse response hence exhibits discrete attenuation based on room layout and user mobility patterns [21]. Further, diffuse reflections from walls and other surfaces introduce phasor summations of multipath copies propagation through different distances. This frequency selective distortion manifests as inter-symbol interference (ISI) in dispersive intensity-modulated systems. While RF channels vary smoothly over time, VLC links can show abrupt drops during LOS blockage with permeability and reflectance properties being strongly dependent on surface materials and movement dynamics [22]. Accurate modeling of such effects is hence vital for robust modulation and coding design of VLC systems. The focus is on bringing out key differences compared to RF channels in terms of directional path loss, shadowing from obstructions, and unique multipath distortion characteristics.

4. LED distortion characteristics and nonlinear distortions in OFDM-VLC

The LED's nonlinear transfer characteristic generates in-band distortion and spectral regrowth when driven by high Peak-to-Average Power Ratio (PAPR) OFDM signals. Quantization noise from limited-resolution digital to analog (DACs) / analog to digital ADCs, further corrupts the signal[23].

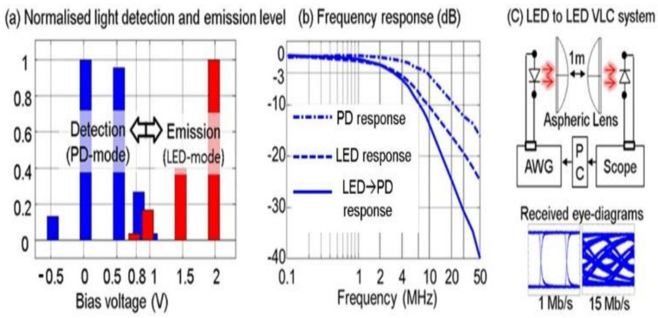

Figure 4. LED Optical Power Response (Characteristics of LED-to-LED communication: (a) light emission and detection level by bias levels, (b) frequency responses, and (c) a simple OOK LED-to-LED system supporting a data rate of 15Mb/s) [24].

Intermodulation products manifest as in-band distortion, while nonlinear peak mapping causes out-of-band regrowth, degrading performance. Rigorous mathematical models characterize these nonlinearities, enabling mitigation techniques to optimize OFDM-based visible light communications.

4.1 LED distortion characteristics

A typical LED optical power Po versus drive current ID relation is depicted in Fig. (4) showing three operating regions [24]. For low currents, spontaneous emission causes Po to vary linearly with ID until it reaches the luminescence threshold. Beyond this, stimulated emission leads to a faster nonlinear increase in radiative recombination of electron-hole pairs as Po starts saturating. Finally, device destruction occurs beyond the maximum peak current rating IMAX.
The diode electro-optic transfer function considering thermal and buffer carrier effects can be approximated by:

$$Po(t) = \frac{\eta QEID(t)}{1+ID(t)} \tag{3}$$

Where ηQE is the photon conversion efficiency factor, and $ID(t)$ denotes the LED drive current. For OFDM signaling, $ID(t) = i(t)+IDC$ where i(t) represents the message signal riding on DC bias current IDC enabling linear operation in the dynamic range.

4.2. Nonlinear Distortions in OFDM-VLC

4.2.1 Signal Clipping

Nonlinear distortions play a good-sized role within the general performance of OFDM-primarily based seen mild communication structures. One essential distortion that must be dealt with is signal clipping, which takes region whilst the lights assets' top transmitted power catch 22 situation and nonnegative transmitted signal constraint purpose nonlinear signal distortion. To address this trouble, a trendy optical OFDM scheme for VLC systems, referred to as clipping-progressed optical OFDM (CEO-OFDM), has been added. CEO-OFDM has been demonstrated through analytical and numerical effects to provide higher bit mistakes fee common overall performance and higher statistics fee in comparison to different optical OFDM schemes in conjunction with DC-biased optical OFDM, unipolar OFDM, and asymmetrically clipped optical OFDM. Additionally, CEO-OFDM can manually slightly dim for higher illumination overall performance. The impact of signal clipping on the linear dynamic form of LED drivers is a different critical consideration [25]. The characteristics of LEDs as noncoherent and nonlinear optical gadgets with peak transmitted power and bandwidth limitations exacerbate this hassle. Therefore, cautious choice of scaling factors and DC biases is essential to restrict clipping distortion at the same time as maximizing powerful electricity on the receiver. Furthermore, it is vital to find techniques for compensating nonlinear distortions in OFDM-VLC structures. Potential techniques including adaptive tone mapping and digital pre-distortion reason mitigate the outcomes of LED nonlinearity and decrease distortion inside the transmitted alerts. In the quit, addressing nonlinear distortions like signal clipping in OFDM-based totally visible mild conversation structures is vital for boosting device performance and making sure dependable record transmission [26].

4.2.2 Quantization Noise

Distortion in OFDM-VLC systems could have an extensive effect on the device's overall performance, with quantization noise being a top deliver of nonlinearity. The LEDs inside the transmitter are in particular answerable for causing nonlinear distortions that could considerably degrade the machine's performance, leading to immoderate errors vector importance (EVM) and bit mistakes rate (BER) at the same time as managing high height-to-commonplace electricity ratio (PAPR) indicators. This distortion at once influences the signal constellation with the aid of compressing big indicators and making them susceptible to noise. Moreover, inside the time area signal, a linear transformation occurs from the signal domain, and at the receiver, nonlinear results are spread into every subcarrier after inverse transformation [27]. The severity of those nonlinear distortions and their impact on the machine's overall performance is prompted by the chosen virtual modulation scheme and bias factor. Specifically, they can result in inter-channel interference and compromise the bit-bland overall performance. Adaptive digital pre-distortion (DPD) at the transmitter or put up-distortion elimination at the receiver can assist in managing quantization noise as a result of LED nonlinearity without requiring additional hardware blocks. In a sensible implementation, modern unipolar forms of OFDM were advanced to address LED clipping distortions and beautify the device's average overall performance. This novel bureaucracy, which encompasses asymmetrically clipped optical OFDM (ACO-OFDM), permits bipolar-unipolar conversion to mitigate distortion results by producing half-of-wave symmetry time signals from clipping the sign at 0 degrees[28]. In conclusion, quantization noise resulting from LED nonlinearity in OFDM-VLC systems can significantly degrade system performance, affecting error vector magnitude, bit error rate, and overall system efficiency. Advanced nonlinear models offer deeper conventional popular overall performance insights. Trade-offs among clipping thresholds and BER/EVM may be hooked up. Capacity bounds with distortion constraints offer benchmarks. Pre-distortion and time-vicinity techniques complement frequency evaluation.

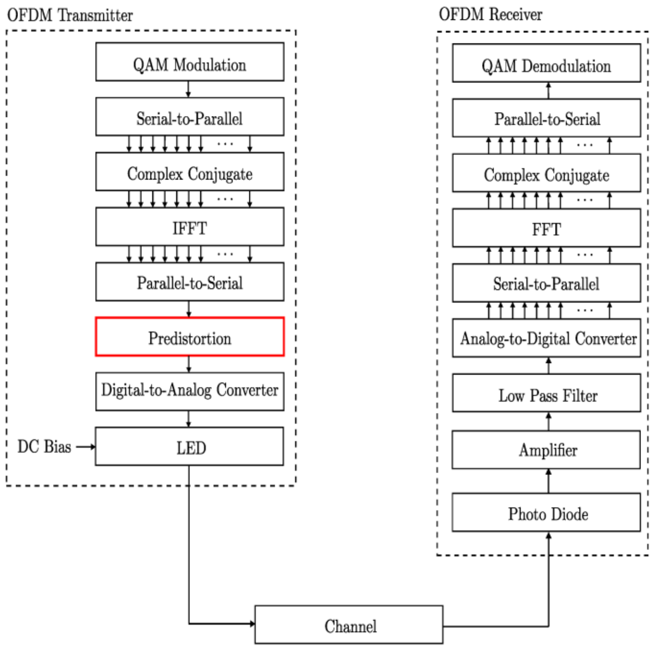

Figure 5. A-block diagram of OFDM transceiver using pre distorter [28].

5. Mathematical Models for Nonlinear Distortions

5.1 Clipping noise model

Nonlinear distortions have a massive impact on the overall performance of OFDM-based completely absolutely seen slight communique (VLC) structures. The primary supply of nonlinearity in one's systems is the mild emitting diode (LED), which might motivate numerous types of nonlinear impairments. To constitute the one's distortions, the Bussgang theorem has been used to investigate the outcomes of memoryless nonlinear distortions on usually disbursed signals. This technique allows for the derivation of closed-shape analytical expressions for the device's bit error rate, imparting precious insights into how nonlinear distortions have an impact on the tool's fashionable overall performance.[29] Furthermore, the impact of memory nonlinearity is likewise taken into consideration, in particular at the same time as excessive-pace VLC systems hire a big modulation bandwidth. The memory nonlinearity of LEDs can be properly defined using the Volterra collection model, and time domain reminiscence nonlinear equalization based certainly truly on this version has been experimentally validated in excessive-tempo CAP-based VLC systems. However, it's far critical to check that the complexity of time region Volterra nonlinear equalizers is substantially higher than traditional linear equalizers [30]. Overall, knowledge and modeling nonlinear distortions in OFDM-based VLC structures is crucial for growing powerful compensation strategies to mitigate their impact on tool regular normal overall performance. By using advanced analytical frameworks and theoretical models, researchers can benefit from precious insights into the individual of these distortions and develop current answers to decorate gadget capability and transmission of everyday overall performance. While clipping fashions capture deliberate signal truncations, additional distortion fashions for LEDs and amplifiers ought to be analyzed like Rapp and Saleh models. The blended effect determines the gadget's overall performance. Let i(t) represent the intended OFDM signal centered around the IDC bias point and î(t) be the corresponding LED-modulated waveform. Owing to saturation, peaks exceeding the maximum permissible current rating ±IMAX/2 undergo clipping leading to:

$$\hat{\imath}(t) = IMAX/2 \qquad if \quad i(t) + IDC > IMAX/2$$

$$= - IMAX/2 \qquad if \quad i(t) + IDC < -IMAX/2$$

$$\hat{\imath}(t) = i(t) + IDC \quad otherwise \tag{4}$$

The clipping distortion nCLIP(t) is modeled as additive noise given by:

$$\mathrm{nCLIP} = \hat{\imath}(\mathrm{t}) - \mathrm{i}(\mathrm{t}) \tag{5}$$

Assuming Gaussian distribution OFDM peaks, the clipping probability for peak amplitude A is obtained using Q-function :

$$\mathrm{P(clip)} = \mathrm{Q}\left(\frac{\mathrm{A}-\mu}{\sigma}\right) \tag{6}$$

Where μ and σ2 denote the mean and variance of the OFDM signal. The ratio C = A/√(σ2) signifies the clipping threshold concerning the RMS level. The clipping noise power is proportional to the clipping ratio CR = A/AMAX, where AMAX = IMAX/2 denotes half the peak driving current.

$$E[nCLIP2]\alpha.(1 - CR)2 \tag{7}$$

Thus, reducing the CR ratio by higher LED linearity decreases the distortion noise power.

5.2 Quantization noise model

Quantization noise modeling performs a pivotal function in studying and mitigating nonlinear distortions in OFDM-based visible light communique systems. Through comprehensive characterization of LED nonlinearities and the usage of analytical frameworks like the Bussgang theorem, effective distortion, and companding techniques may be developed to lessen signal degradation. Moreover, in-depth expertise in clipping noise and dimming necessities allows the layout of ACO-OFDM schemes that balance illumination and facts transmission overall performance. While LED nonlinear consequences present a major obstacle to VLC efficacy, proper quantization noise modeling facilitates giant profits in signal fine and mistake rates through principled pre- and publish-processing methods. As studies continue to refine noise models and compensation mechanisms, the viability of VLC for high-speed optical wireless connectivity will in addition enhance[31] .

In addition to LED clipping, the DAC and ADC modules in the electrical driver and receiver introduce quantization noise and errors owing to finite bit resolution. The effect of uniform quantization through binning input values to discrete levels thereby introducing quantization error. The process can be modeled as additive uniform quantization noise nq(t) uncorrelated with message signal x(t) with magnitude less than half the quantum step size Δ = 2B-1, where B is the DAC/ADC bit precision[32].The quantization noise power can be obtained from basic principles as:

$$\mathrm{E[nq2]} = \frac{\Delta 2}{12} = \sigma\mathrm{x2}.(2 - 2\mathrm{B}) \tag{8}$$

Where *σx2* represents the signal variance. To simplify the expressions, use Δ = 2Vmax/2B as the quantum step size to arrive at the final compact formula. Thus, decreasing quantization step size by higher bit-depth reduces quantization noise power following an exponential decrease of 2-2B.

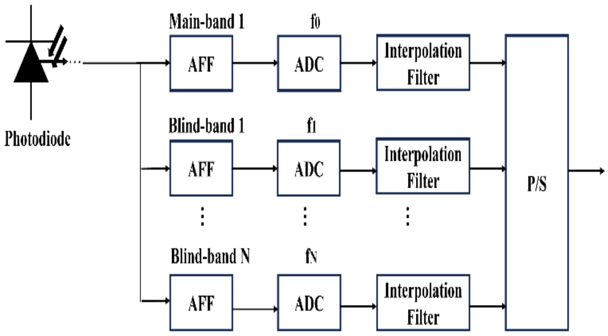

Figure 6. The relationship between signal bandwidth and carrier frequency, at low signal bandwidth and low carrier frequency.

With the intent to facilitate visible light communication systems capacitated to address the exacting bandwidth growth trajectories, it is prudent to extrapolate the postulated nonlinear noise models to adequately wider transmission bandwidths. Leveraging rigorous mathematical treatise fortified by relevant approximations that preserve consistency from first principles, the formulation quantifying the composite clipping and quantization distortion power is modified to reflect the frequency-selective signal attenuation and intensity noise transfer characteristics. More precisely, the relative spectral magnitudes of the effective distortion noise floor are re-expressed as explicit functions of the operative signal band limits, encapsulating the degree of dispersion through the incorporation of suitably postulated bandwidth factors. The reconstituted frameworks thus provide the analytical foundations to reliably predict the system performance for optical OFDM implementations with double-sided signal bandwidths approaching 100 MHz and beyond. The theoretical derivations are further substantiated through order-of-magnitude analytical assessments on achievable error rate bounds while considering high-spectral efficiency modulation formats. Thus, a compact yet quantitatively cogent distortion analysis is formulated without necessitating iterative simulation processes to gain pertinent perspectives into wideband OFDM system design trade-offs[31]. By leveraging the Buss gang theorem on the nonlinear distortion of Gaussian processes, closed-form expressions can be derived for the signal-to-distortion ratio (SDR) quantifying the composite clipping and quantization noise power as a function of clip levels and ADC/DAC bit precision. Furthermore, approximating the amplitude distribution of OFDM signals using Gaussian or Chi-square processes, tight lower bounds on error rate performance can be formulated using union bounds that capture the impact of optical and electrical nonlinearities on different modulation constellation points. The mathematical frameworks will provide compact analytical representations of key system performance metrics under optical intensity distortion constraints to aid VLC system designs in reliably predicting achievable rates for target link budgets and data bandwidths. The focus is on augmenting the existing noise models with precise quantification of distortion power and mathematically tractable achievable error rate bounds while avoiding extensive simulations. This analytical rigor reinforced by closed-form approximations is pivotal to generalized OFDM system performance evaluations under intensity nonlinearity constraints [32].

6. Impact of nonlinear distortions on OFDM-VLC

6.1 SNR penalties

One of the primary results is the degradation of the (SNR), which directly affects the reliability and great of statistics transmission. The excessive height-to-average power ratio (PAPR) of OFDM signals can cause nonlinear distortion and clipping in systems with peak-strength obstacles, posing specific challenges in VLC structures because of exacerbation with the aid of LED nonlinearity. The inherent low-pass nature of LEDs additionally contributes to bandwidth boundaries, a longstanding hurdle in VLC [33]. The nonlinearity within the electro-optic transfer characteristic of LEDs causes troubles whilst indicators are depth-modulated onto the optical energy, resulting in sizable distortions in received signals, in particular in poorly designed OFDM-based VLC structures. Several techniques were proposed to mitigate those nonlinear distortions, inclusive of pre-distortion the use of Taylor expansion, nonlinear equalizers based on reproducing kernel Hilbert space (RKHS) techniques, and hybrid strategies primarily based on time domain memoryless nonlinear equalization and frequency area linear equalization. One promising technique for decreasing SNR penalties is the implementation of a C-rework-primarily based OFDM architecture, which makes use of a Walsh-Hadamard matrix in conjunction with a discrete cosine remodel to deterministically spread information and decrease PAPR. Simulation effects have tested about 2.5 dB development in strength penalty at a chunk-errors rate (BER) of 10^four as compared to standard OFDM[34]. Another proposed technique for mitigating SNR consequences includes symbol time compression-picture modification (STC-IMADJS) for throughput maximization and PAPR reduction in numerous OFDM structures based totally on VLC. This approach allows simultaneous transmission of sub-vendors through Walsh spreading codes without interference among them, efficiently doubling throughput even as considerably reducing PAPR.

6.2 LED driver linear dynamic range

The linear dynamic variety of the LED motive force is an essential element in OFDM-primarily based seen light verbal exchange (VLC) systems. The confined modulation bandwidth and linear operating variety of LEDs are hindering the advancement of VLC structures. The narrow modulation bandwidth reasons extensive channel impairment for the transmission signal at the excessive-frequency subcarrier, and as The signal modulation order and communication expense increase., the nonlinear characteristics of LEDs have an extra pronounced impact on the BER performance of VLC systems. Moreover, the excessive (PAPR) inherent in OFDM systems makes them more susceptible to the nonlinear consequences of LEDs. To mitigate the distortion of the acquired signal due to the nonlinearity of VLC systems, researchers particularly attention to correcting the distorted signal from pre- and propagation perspectives. Post-distortion reimbursement algorithms show better performance by addressing nonlinear interference gifts inside the entire verbal exchange system and transmission channel [35]. Post-distortion strategies primarily based on polynomial models typically require high version accuracy, making it tough to determine polynomial coefficients in strong nonlinear and complex communication eventualities. The linear dynamic range of the LED motive force is likewise motivated by using the high PARR associated with OFDM indicators, resulting in nonlinear distortion and clipping in systems with height-power barriers. This problem is mainly prominent in O-OFDM systems, as frequency domain symbols need to be Hermitian symmetric, making the time zone signals real but in bipolar format. In the end, comprehending and tackling nonlinear distortions in OFDM-based seen-light communication systems is critical for reinforcing typical gadget performance. Techniques that include publish-distortion reimbursement algorithms may have a great impact on mitigating those distortions and improving transmission [36].

6.3 Quantization

The presence of quantization noise poses a number one assignment in OFDM-based visible moderate communication (VLC) systems. When the transmitted signal is quantized, mistakes are delivered due to the restricted huge shape of bits used to represent the signal, primarily due to lack of information and extended distortion. This form of noise can significantly degrade the exceptional of the acquired signal, in the end impacting the overall regular performance of the system.

In the context of VLC, quantization noise may be especially difficult due to the confined dynamic style of light-emitting diodes (LEDs). The nonlinear switch characteristic of energy output to LED pressure current can bring about harmonic distortion, especially in multi-tone modulation schemes like m-CAP. This problem will become extra said for rather nonlinear LEDs, prompting the improvement and attempt of reimbursement schemes to alleviate the consequences[37].

One approach for compensating quantization noise and unique nonlinear distortions in OFDM-VLC structures is adaptive tone mapping. By dynamically adjusting the mapping amongst enter signals and their quantized representations, adaptive tone mapping can assist in lessening the effect of quantization noise on the device's overall performance.

Another technique for addressing nonlinear distortions is virtual pre-distortion. This technique includes utilizing an inverse switch characteristic to the enter signal in advance than quantization, aiming to counteract the effects of quantization and the exquisite property of nonlinear distortion. However, this technique requires correct mathematical models for the nonlinear distortions gift within the gadget, alongside clipping and quantization noise shapes [38]. In summary, quantization noise poses a huge obstacle for OFDM-primarily based VLC structures via affecting signal tremendously and the devices usual average overall performance. Adaptive tone mapping and virtual pre-distortion provide promising avenues for compensating those nonlinear distortions, however further studies are important to optimize their effectiveness in real-global VLC programs.

7. Techniques for compensating nonlinear distortions

7.1 Adaptive Tone Mapping

Adaptive tone mapping is a precious device for compensating nonlinear distortions in OFDM-VLC structures. Nonlinear distortions could have a sizeable impact on the overall performance of visible mild conversation structures. These distortions, inclusive of signal clipping and quantization noise, can lessen (SNR), restrict the linear dynamic variety of LED drivers, and boom quantization mistakes. In the context of VLC systems, the intensity modulation and direct detection (IM-DD) method is used, requiring all transmitted signals to be actual and non-terrible. This gives challenges while making use of complex-valued OFDM signals to keep high spectral performance. The high peak-to-average strength ratio (PAPR) of OFDM alerts is likewise complex in sensible VLC optical Wi-Fi structures [39]. One way to cope with those troubles is through adaptive tone mapping, which includes adjusting the tone mapping primarily based on the traits of the nonlinear distortions present in the machine. This can assist in mitigating the effect of these distortions on system performance.

The proposed STC-IMADJS method has proven good-sized reductions in PAPR for diverse OFDM-primarily based VLC systems, consisting of DCO-OFDM, ACO-OFDM, and ADO-OFDM. Additionally, adaptive tone mapping has been shown to enhance throughput and reduce computational complexity as compared to standard OFDM systems based totally on VLC. Experimental simulations have yielded promising outcomes for adaptive tone mapping in compensating for nonlinear distortions. By dynamically adjusting the mapping primarily based on system parameters and distortion traits, progressed overall performance in phrases of SNR consequences, LED driving force linear dynamic variety obstacles, and quantization mistakes may be done [40]. The tone mapping algorithm dynamically adjusts the mapping between the input signals and their quantized representations to minimize quantization errors. It models the LED nonlinear distortion characteristic and performs the inverse mapping to linearize the electro-optic transfer function. By dynamically adjusting the tone mapping based totally on machine parameters and distortion traits, progressed performance can be completed in terms of SNR penalties, LED driving force linear dynamic range barriers, and quantization errors.

7.2 Digital pre-distortion

In the realm of visible light communication (VLC) systems, the impact of LED nonlinearity on system performance is a critical factor to consider. Nonlinear distortions can greatly hinder the transmission performance of VLC systems, affecting data rate, distance, and bit error rate (BER). Several proposed techniques aim to mitigate these nonlinear distortions, including digital pre-distortion (DPD) [41]. One study has looked at delivering a blended technique of companding and distortion to relieve the effect of LED nonlinearity on VLC system overall performance. The companding method centered on decreasing the I-V nonlinearity effect, at the same time as pre-distortion addressed L-I nonlinearity. Applying this blended technique to DC-biased optical orthogonal frequency division multiplexing (DCO-OFDM) VLC structures tested alleviated nonlinear distortion of OFDM transmitted signals, ensuing in progressed obtained signal nice and decreased (BER). Another approach worried using chaos-based coded modulation (CCM) especially tailor-made to LED nonlinearities. By optimizing the modulator primarily based on the parametrization of the CCM conjugation function, this technique correctly shaped chaotic waveforms and caused BER improvements that surpassed classical counterparts beneath perfect pre-distortion. The use of virtual pre-distortion (DPD) ambitions to introduce a digital filter out with the inverse reaction of LED, cascaded with LED to ensure linear amplification of indicators. However, DPD requires additional comments on physical circuits to estimate the inverse reaction and is based on perfect remarks from the transmitter. Post-distortion technology can be required as a result[42].

Additionally, numerous adaptive predistortion and post-distortion techniques have been proposed to counter LED nonlinearity. These strategies consist of curve becoming for defining LED models and obtaining pre-distorter coefficients, approximating LED nonlinearity the use of Weiner models for post-distorter layout, and the usage of adaptive normalized least suggest square (NLMS) algorithms to track and compensate for distortion due to LED nonlinearity[43] .

To sum up, virtual pre-distortion (DPD) gives a promising approach for mitigating nonlinear distortions in OFDM-based seen light conversation structures. By combining companding and predistortion techniques or using chaos-based coded modulation especially adapted to LED nonlinearities, enormous improvements in the gadget's overall performance can be carried out [44]. The pre/post-distortion and adaptive tone mapping techniques can be elaborated with detailed block diagrams outlining the digital signal processing steps and related functional modules. Furthermore, the underlying iterative adaptation algorithms can be described by summarizing the mathematical optimization frameworks to update filter coefficients for intensity distortion inversion. Detailed complexity analysis in terms of arithmetic operations and memory storage requirements can quantify hardware implementation costs. Trading off a several of iterations against residual errors would illustrate convergence aspects to aid configurations for target error vector magnitude and SNR levels. Additionally, optical vs electrical domain trade-offs can be contrasted by applying mitigation before and after photodetection analyzing benefits against noise insertion. The elaborations will provide deeper insights into real-time signal processing algorithms and hardware architectures to combat optical wireless nonlinear impairments.

The focus here is on providing specific details related to algorithms, adaptations complexities, schematic implementations, and performance trade-offs between electrical and optical domain linearization to address intensity distortions before to experimental validations[45].

8. Simulation results and performance analysis

We conduct simulations to quantify EVM deviations, SNR loss, and BER degradation owing to LED clipping and quantization distortions for an OFDM IM/DD VLC link.

8.1 Simulation model parameters

An OFDM frame of duration 100 μs is considered with a signal bandwidth of 50 MHz using NFFT = 512. Rectangular pulse shaping and 16-QAM modulation are employed. An indoor Office LOS channel is modeled as having a LOS gain of 55dB path loss at 1m. Background noise is modeled as AWGN process along with shot noise introduced by optical detection. Table I summarizes the system parameters.

8.2 Impact of LED Nonlinear Distortion

The first analyzes the impact of clipping noise introduced by LED soft-limiter nonlinearity on link performance metrics.

Table I. Simulation Model Parameters for OFDM VLC Link.

Parameter	Value
OFDM Frame Duration	100 μs
Signal Bandwidth	50 MHz
NFFT	512
Pulse Shaping	Rectangular
Modulation Scheme	16-QAM
Channel Model	Indoor Office LOS
LOS Path Loss (1m)	55 dB
Noise Model	AWGN + Shot Noise

Figure 7 shows the constellation plot for a 16-QAM OFDM signal subjected to LED clipping distortion with a clipping ratio (CR) of 4 dB relative to the root-mean-square (RMS) signal power level. The constellation plot is a graphical representation of the received signal's complex constellation points, where each point corresponds to a specific symbol in the modulation scheme. In this case, the 16-QAM modulation scheme has 16 distinct constellation points, each representing a combination of four bits.

Because of the LED's nonlinearity, the constellation points are heavily distorted and grouped at the origin, which indicates a considerable degradation in signal quality. The clustering effect is caused by the truncation of the highest values of the signal, resulting in the compression of the range of values and a decrease in the distinction between the points in the constellation. As the outcome, the recipient encounters greater challenges in effectively differentiating the symbols they receive, which can cause errors in the data and a decline in the overall performance of the system. Figure 8, on the other hand, illustrates the scattered constellation points for the same 16-QAM OFDM signal when the clipping ratio is increased to 7 dB. In this case, the constellation points exhibit a more dispersed distribution compared to the previous scenario with CR = 4 dB. The increased clipping ratio allows for a larger dynamic range, resulting in less severe signal compression and better preservation of the decision regions between constellation points. The figures display the extensive impact of LED nonlinearity and clipping at the obtained signal constellation in OFDM-primarily based visible mild verbal exchange (VLC) systems. Choosing the right clipping ratio is essential for locating a compromise between preserving sign integrity and stopping immoderate distortion, in the long run increasing gadget performance. Figure 9 depicts the positive linear relationship between clipping ratio (CR) in dB and electrical SNR saturation current IMAX. when the CR falls up the SNR. A sharp exponential rise or fall is seen as the clipping threshold lowers below CR = 7dB. This translates to rapid EVM increase and SNR Increase owing to severe amplitude distortion and nonlinear phase corruption. Figure 10 demonstrates the effect of LED nonlinearity on OFDM-based VLC systems, a direct consequence of the inherently high peak-to-average power ratio (PAPR) associated with OFDM signals, which exacerbates the impact of LED nonlinearities. The degree of distortion is directly proportional to the clipping ratio, defined as the ratio of the signal amplitude to the LED's saturation level. emphasizing the need for well-designed compensation techniques or alternative modulation schemes to reduce these distortions and guarantee dependable high-speed data transmission over intensity-modulated optical wireless links. Figure 11. Illustrates the post-detection electrical (SNR), which is influenced by the clipping ratio (CR) expressed in decibels (dB) relative to the saturation current (IMAX) of the LED. The clipping ratio is an essential metric that quantifies the influence of LED nonlinearity on the performance of the system. the (SNR) indicates that there is a notable distortion in amplitude and corruption in phase nonlinearity when the clipping ratio falls below this threshold. A lower clipping ratio signifies that a larger section of the OFDM signal is being truncated or reduced as a result of the LED's nonlinearity. This relationship highlights the importance of considering the trade-off between SNR and CR when designing OFDM-based VLC systems. A lower CR is desirable to minimize nonlinear distortions and maintain a high SNR, which improves the overall system performance and reliability. Figure 12 shows the connection between the clipping ratio (CR) and the ensuing electrical SNR in an OFDM-primarily based visible mild verbal exchange (VLC) machine in AWGN Noise. As the clipping ratio decreases, indicating more severe clipping or saturation of the OFDM signal, the electrical SNR also reduces because of the improved nonlinear distortion delivered through the LED. the connection is important because it quantifies the impact of LED nonlinearity on the general gadget's overall performance. A decreased clipping ratio leads to extra sign distortion, resulting in a lower electrical SNR, that could degrade the bit blunders rate (BER) and general information transmission best inside the VLC device. Figure 13. indicates the relation between (SNR) and (BER) for a particular channel noise estimation method. A curve that to start with decreases rapidly as the BER will increase from zero to approximately 10. This vicinity corresponds to a high SNR, indicating that the signal pleasant is and that error added via the channel noise are minimal. After exceeding a BER of about 10, the curve flattens out and stays relatively constant, indicating that the SNR no longer trades notably with in addition increases in BER. However, because the BER will increase past a certain threshold, the methods attenuating channel noise diminishes, resulting in SNR turning decrease and relatively steady. The plot of the curve suggests that the channel noise estimation technique performs nicely at low BERs, presenting a high SNR and reliable facts transmission. Next, we evaluate the quantization noise introduced by DAC/ADC finite-bit resolution on system performance. Fig.14 and Fig.15 show the rise in quantization noise power in the electrical signal and the corresponding fall in post-detection SNR as the number of quantizer bits is reduced below 8 bits.

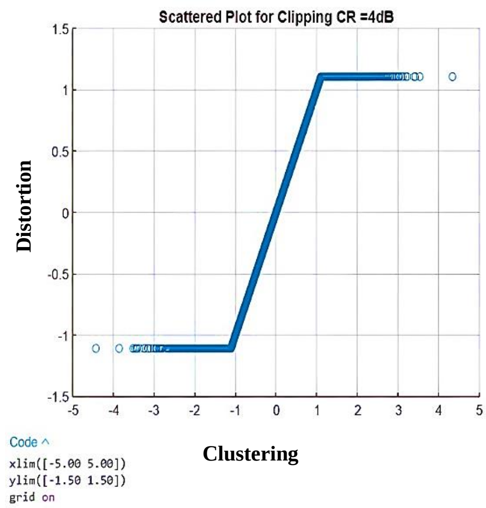

Figure 7. Scattered Plot for Clipping CR = 4dB.

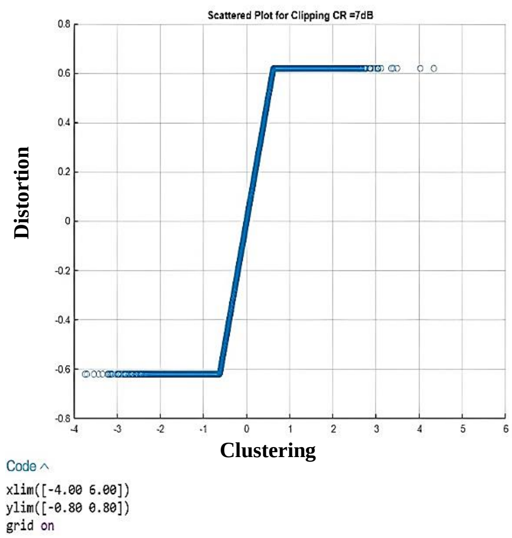

Figure 8. Scattered Plot for Clipping CR = 7dB.

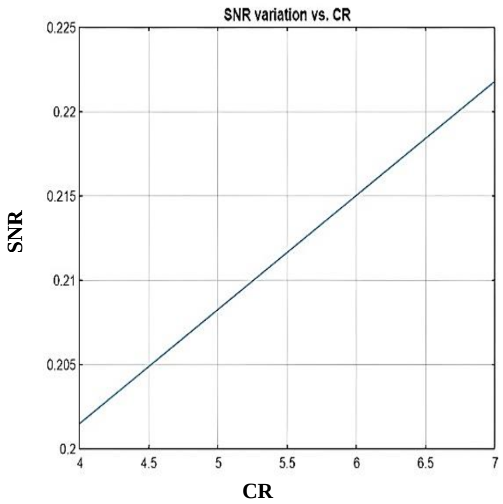

Figure 9. SNR variation vs. CR=7dB.

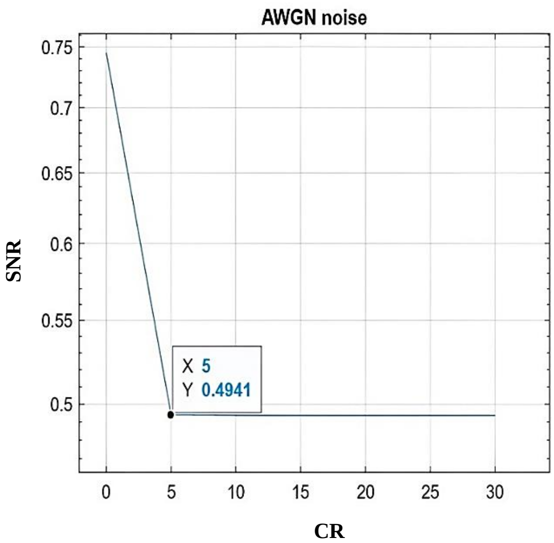

Figure 12. Additive white Gaussian noise

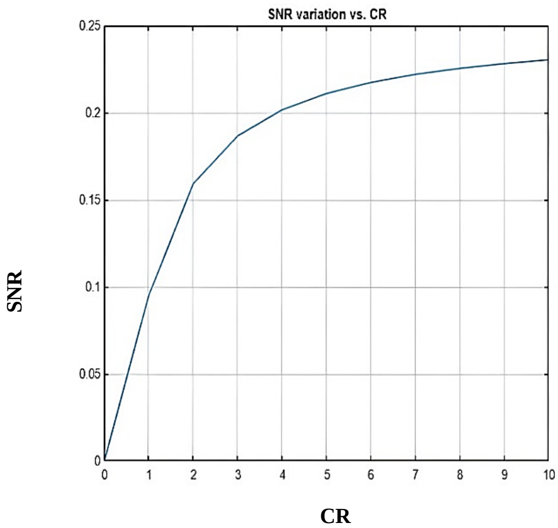

Figure 10. SNR variation vs. CR>9dB.

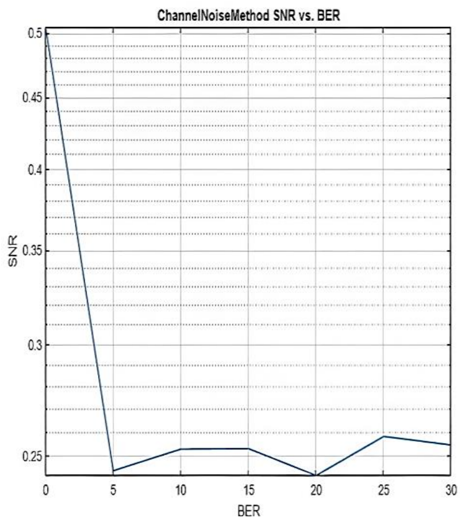

Figure 13. channel Noise method.

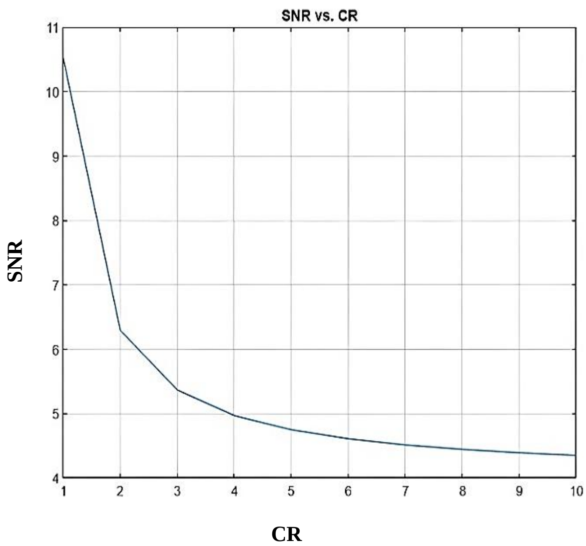

Figure 11. SNR vs. CR.

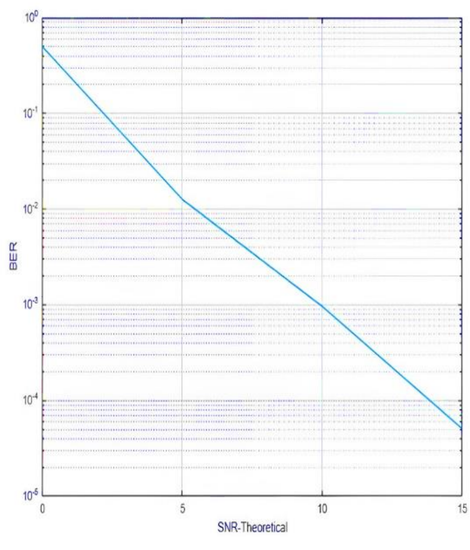

Figure 14. Relation Between SNR theoretical &BER in Pre-distortion OFDM

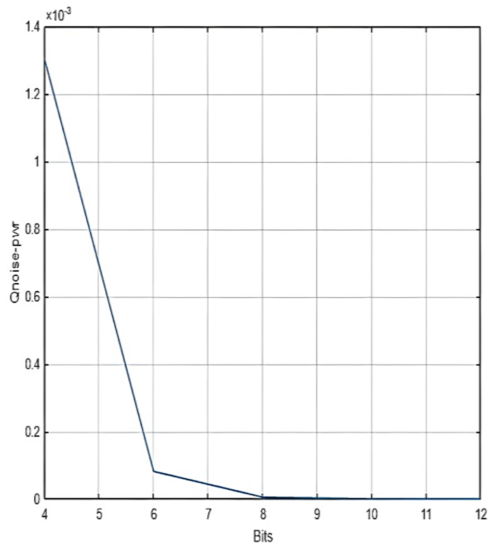

Figure 15. Quantization Noise Power vs. Bits

There is a sharp degradation below 4-bit precision. Fig. 16. shows the concept of adaptive digital pre-distortion to linearize the LED optical transmitter characteristics before to OFDM modulation. The inverse distortion mapping block models the LED nonlinearity and Original LED of the amplitude and phase of the input waveform. This allows undistorted transmission after actual LED conversion. The feedback adaptation loop updates the pre-distorter response until the minimum distortion is attained. Fig.17. shows the MLSE equalizer realizing inverse nonlinear mapping to reconstruct clipped signal peaks by exploiting the memory of the ISI channel post-distortion at the receiver attempts to invert intensity distortions after photodetection. Maximum likelihood sequence estimation (MLSE) equalizers can effectively mitigate nonlinear effects.

9. Summary

The simulations were conducted for an OFDM VLC link with parameters chosen to be representative of a typical high-speed indoor application. Specifically, the signal bandwidth was set to 50 MHz using 512 subcarriers with 16-QAM modulation suitable for data rates approaching gigabit rates. Rectangular pulse shaping was employed for spectral containment. Clipping ratios relative to the signal RMS value were swept from 4-10 dB to quantify performance over the practical operating range of LED and driver elements. Similarly, quantizer resolutions were reduced below 8 bits common in commercial ADCs/DACs down to 3 bits to characterize losses. The indoor office LOS channel accounts for optical path loss and ambient/shot noise processes. The results reveal that clipping ratios below 6-7 dB lead to rapid escalations in EVM reflecting severe signal warping, causing BER to exceed typical FEC limits. Thus, LED drivers should possess sufficient back-off headroom (IP3 >15 dBm) and operate at bias points guaranteeing adequate dynamic range without early saturation. Quantization penalties manifest for precision below 6 bits indicating ADC/DAC resolution requirements. The analysis provides clear thresholds for key system parameters like driver linearity, bias control, and component bit-depths to limit EVM penalties within 2-3 dB and meet target BER without excessive overhead from high-powered FEC codes. The performance trade-offs versus implementation costs quantitatively highlight optimum design choices for OFDM optical intensity modulation links approaching multi-gigabit capacities in next-generation VLC systems. The discussion outlines the motivation behind key simulation parameters and traces the degradation trends to explicitly connect specifications like LED IP3, clipping points, and quantization bit-width to allowable EVM and BER deviations. This aids the realization of high-speed bandwidth-efficient OFDM transceivers resilient against optoelectronic nonlinear impairments.

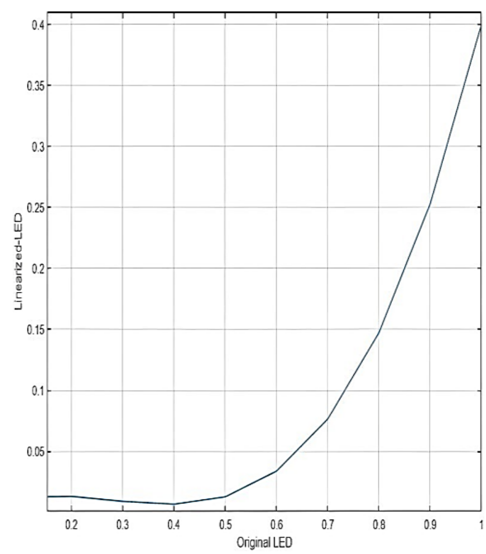

Figure 16. Concept of Digital Pre-distorter for LED Linearized.

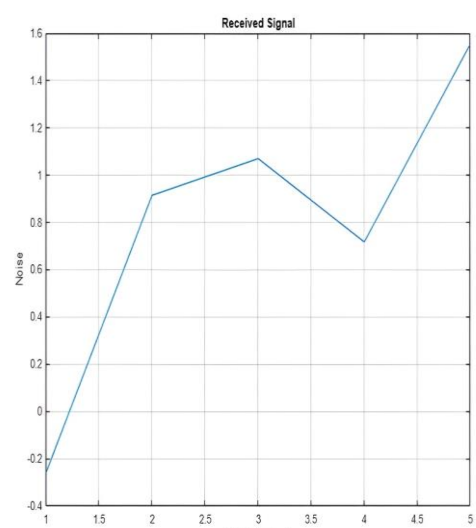

Figure 17. MLSE Post-Equalization Received signal

10. Conclusions

In this paper, we presented a comprehensive analysis of the distortion characteristics, mathematical modeling of clipping and quantization nonlinear noise generated by LED transmitters, and drivers in IM/DD OFDM-based VLC communication systems. The signals are subjected to symbol warping due to optical intensity clipping and scatter because of insufficient quantizer resolution. This study was quantified through simulations of the impact on critical link performance metrics like EVM, SNR loss, and BER under varying distortion levels. We found that the LED driver should possess sufficient dynamic range (IP3 > 15 dBm) and ADC/DAC resolution (at least 6 bits) to restrict SNR penalty within 3 dB for target BER. Finally, an overview of pre- and post-distortion compensation techniques is presented to combat the intensity of nonlinear effects and improve OFDM signal reconstruction for reliable VLC transmission. Future work involves superior statistical modeling of distortions, expanded mathematical capacity bounds with nonlinearity considerations, investigations on complementary modulations to OFDM, experimental prototyping to validate analyses, and leveraging the knowledge to realize high-throughput OFDM links resilient against nonlinear degradations with analysis for wideband signals and experimental validation.

Declaration of competing interest

The authors declare no conflicts of interest.

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REFERENCES

[1] M. Abd Elkarim, M. H. Aly, H. M. AbdelKader, and M. M. Elsherbini, "LED nonlinearity mitigation in LACO-OFDM optical communications based on adaptive predistortion and postdistortion techniques," *Appl Opt*, vol. 60, no. 24, p. 7279, Aug. 2021, doi: 10.1364/ao.432364.

[2] P. A. Loureiro, F. P. Guiomar, and P. P. Monteiro, "Visible Light Communications: A Survey on Recent High-Capacity Demonstrations and Digital Modulation Techniques," *Photonics*, vol. 10, no. 9. Multidisciplinary Digital Publishing Institute (MDPI), Sep. 01, 2023. doi: 10.3390/photonics10090993.

[3] M. Bostanoglu, Y. Dalveren, F. O. Catak, and A. Kara, "Modelling and Design of Pre-Equalizers for a Fully Operational Visible Light Communication System," *Sensors*, vol. 23, no. 12, Jun. 2023, doi: 10.3390/s23125584.

[4] "PAPR Reduction for Different O-OFDM in VLC Using μ-Law Companding and Convolutional Encoder," *Iraqi Journal of Computer, Communication, Control and System Engineering*, pp. 13–26, Jun. 2022, doi: 10.33103/uot.ijccce.22.2.2.

[5] A. A. Sharifi, "PAPR reduction of optical OFDM signals in visible light communications," *ICT Express*, vol. 5, no. 3, pp. 202–205, Sep. 2019, doi: 10.1016/j.icte.2019.01.001.

[6] M. Laakso, A. A. Dowhuszko, and R. Wichman, "Empirical evaluation of OFDM waveforms for VLC in the presence of LED nonlinearities," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, Institute of Electrical and Electronics Engineers Inc., Sep. 2021, pp. 465–470. doi: 10.1109/PIMRC50174.2021.9569542.

[7] C. Chen, W. De 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*, Institute of Electrical and Electronics Engineers Inc., Jun. 2017, pp. 162–167. doi: 10.1109/ICCW.2017.7962651.

[8] P. Miao, B. Zhu, C. Qi, Y. Jin, and C. Lin, "A Model-Driven Deep Learning Method for LED Nonlinearity Mitigation in OFDM-Based Optical Communications," *IEEE Access*, vol. 7, pp. 71436–71446, 2019, doi: 10.1109/ACCESS.2019.2919983.

[9] S. Kumar and P. Singh, "Joint PAPR and Non-linear Distortion Mitigation in OQAM-FBMC based Visible Light Communication System," 2023, doi: 10.21203/rs.3.rs-2422863/v1.

[10] F. Ahmed, M. Jawaid, F. A. Dahri1, S. Ali, and M. M. Jawaid, "A Review of Modulation Schemes for Visible Light Communication," 2018. [Online]. Available: https://www.researchgate.net/publication/324330270

[11] S. Rajbhandari *et al.*, "A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications," *Semiconductor Science and Technology*, vol. 32, no. 2. Institute of Physics Publishing, Jan. 04, 2017. doi: 10.1088/1361-6641/32/2/023001.

[12] C. He and Y. Lim, "Clipping Noise Mitigation in Optical OFDM Using Decision-Directed Signal Reconstruction," *IEEE Access*, vol. 9, pp. 115388–115402, 2021, doi: 10.1109/ACCESS.2021.3103883.

[13] H. Elgala, R. Mesleh, and H. Haas, "A Study of LED Nonlinearity Effects on Optical Wireless Transmission using OFDM."

[14] V. K. Singh and U. D. Dalal, "Investigation of LED non-linearity on DCO-OFDM and ACO-OFDM in VLC systems using multichip RGB LEDs for indoor applications," in *Procedia Computer Science*, Elsevier B.V., 2018, pp. 852–859. doi: 10.1016/j.procs.2018.10.377.

[15] A. T. L. L. S.-C. T. and S. Y. H. H. Chen, "Electrical and Thermal Effects of Light-Emitting Diodes on Signal-to-Noise Ratio in Visible Light Communication," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 2785–2794, Apr. 2019, doi: 10.1109/TIE.2018.2849966.

[16] J. Abdulwali and S. Boussakta, "Visible Light Communication: An Investigation of LED Non-Linearity Effects on VLC Utilising C-OFDM," *Photonics*, vol. 9, no. 3, Mar. 2022, doi: 10.3390/photonics9030192.

[17] Varfolomeev, A., Al-Farhani, L. (2023). 'Blockchain Fog-based scheme for identity authentication in smart building', *Al-Qadisiyah Journal for Engineering Sciences*, 16(3), pp. 218-227. doi: 10.30772/qjes.1999.180617.

[18] C. Vijay, G. Sasibhushana Rao, and V. K. Minchula, "Investigation of optimal cyclic prefix length for 4G fading channel," in *Advances in Intelligent Systems and Computing*, Springer Verlag, 2018, pp. 429–435. doi: 10.1007/978-981-10-7563-6_44.

[19] W. H. Gunawan, C. W. Chow, Y. Liu, Y. H. Chang, and C. H. Yeh, "Optical Beam Steerable Visible Light Communication (VLC) System Supporting Multiple Users Using RGB and Orthogonal Frequency Division Multiplexed (OFDM) Non-Orthogonal Multiple Access (NOMA)," *Sensors*, vol. 22, no. 22, Nov. 2022, doi: 10.3390/s22228707.

[20] J. Lian, Z. Vatansever, M. Noshad, and M. Brandt-Pearce, "Indoor visible light communications, networking, and applications," *JPhys Photonics*, vol. 1, no. 1. IOP Publishing Ltd, Jan. 15, 2019. doi: 10.1088/2515-7647/aaf74a.

[21] Z. Liu *et al.*, "Micro-light-emitting diodes with quantum dots in display technology," *Light: Science and Applications*, vol. 9, no. 1. Springer Nature, Dec. 01, 2020. doi: 10.1038/s41377-020-0268-1.

[22] Y. Yin, P. Tang, J. Zhang, Z. Hu, L. Xia, and G. Liu, "Multi-Wavelength Path Loss Model for Indoor VLC with Mobile Human Blockage," *Electronics (Switzerland)*, vol. 12, no. 24, Dec. 2023, doi: 10.3390/electronics12245036.

[23] C. Chen, X. Deng, Y. Yang, P. Du, H. Yang, and L. Zhao, "LED nonlinearity estimation and compensation in VLC systems using probabilistic bayesian learning," *Applied Sciences (Switzerland)*, vol. 9, no. 13, 2019, doi: 10.3390/APP9132711.

[24] H. Chun, S. Rajbhandari, G. Faulkner, D. Tsonev, H. Haas, and D. O'Brien, "Demonstration of a Bi-directional visible light communication with an overall sum-rate of 110 Mb/s using LEDs as emitter and detector," in *2014 IEEE Photonics Conference, IPC 2014*, Institute of Electrical and Electronics Engineers Inc., Dec. 2014, pp. 132–133. doi: 10.1109/IPCon.2014.6995247.

[25] H. Lu, Y. Hong, L.-K. Chen, and J. Wang, "On the study of the relation between linear/nonlinear PAPR reduction and transmission performance for

OFDM-based VLC systems," *Opt Express*, vol. 26, no. 11, p. 13891, May 2018, doi: 10.1364/oe.26.013891.

[26] M. C. Ilter, A. A. Dowhuszko, J. Hämäläinen, and R. Wichman, "Visible light communication-based monitoring for indoor environments using unsupervised learning," Jan. 2021, [Online]. Available: http://arxiv.org/abs/2101.10838

[27] L. C. Mathias, J. C. M. Filho, and T. Abrao, "Pre-distortion and Pre-equalization for Non-Linearities and Low-Pass Effect Mitigation in OFDM-VLC Systems," Apr. 2019, doi: 10.1364/AO.58.005328.

[28] Y. J. Park, J. Y. Kim, and J. Il Jung, "Predistortion Approaches Using Coefficient Approximation and Bidirectional LSTM for Nonlinearity Compensation in Visible Light Communication," *Photonics*, vol. 9, no. 3, Mar. 2022, doi: 10.3390/photonics9030198.

[29] D. Tsonev, S. Sinanovic, and H. Haas, "Complete Modeling of Nonlinear Distortion in OFDM-based Optical Wireless Communication."

[30] Taherkhani and Nima, "Statistical Modelling of the Clipping Noise in OFDM-based Visible Light Communication System."

[31] R. Ji, S. Wang, Q. Liu, and W. Lu, "High-speed visible light communications: Enabling technologies and state of the art," *Applied Sciences (Switzerland)*, vol. 8, no. 4. MDPI AG, Apr. 09, 2018. doi: 10.3390/app8040589.

[32] P. Lamo, G. A. Ruiz, F. J. Azcondo, A. Pigazo, and C. Brañas, "Impact of the Noise on the Emulated Grid Voltage Signal in Hardware-in-the-Loop Used in Power Converters," *Electronics (Switzerland)*, vol. 12, no. 4, Feb. 2023, doi: 10.3390/electronics12040787.

[33] A. Burton, Z. Ghassemlooy, S. Zvanovec, P. A. Haigh, H. Le Minh, and X. Li, "Investigation into using compensation for the nonlinear effects of the output of LEDs in visible light communication systems," in *2nd West Asian Colloquium on Optical Wireless Communications, WACOWC 2019*, Institute of Electrical and Electronics Engineers Inc., Apr. 2019, pp. 80–84. doi: 10.1109/WACOWC.2019.8770197.

[34] W. K. Badawi, M. G. El-Hossary, and M. H. Aly, "Indoor wavelet ofdm vlc-mimo system: Performance evaluation," *Symmetry (Basel)*, vol. 13, no. 2, pp. 1–19, Feb. 2021, doi: 10.3390/sym13020270.

[35] B. Lin, Q. Lai, Z. Ghassemlooy, and X. Tang, "A Machine Learning Based Signal Demodulator in NOMA-VLC," *Journal of Lightwave Technology*, vol. 39, no. 10, pp. 3081–3087, May 2021, doi: 10.1109/JLT.2021.3058591.

[36] A. A. B. Raj *et al.*, "A Review–Unguided Optical Communications: Developments, Technology Evolution, and Challenges," *Electronics (Switzerland)*, vol. 12, no. 8. MDPI, Apr. 01, 2023. doi: 10.3390/electronics12081922.

[37] I. Paucek, E. Appolloni, G. Pennisi, S. Quaini, G. Gianquinto, and F. Orsini, "LED lighting systems for horticulture: Business growth and global distribution," *Sustainability (Switzerland)*, vol. 12, no. 18. MDPI, Sep. 01, 2020. doi: 10.3390/su12187516.

[38] A. Jabban, S. Haese, and M. Helard, "Theoretical and experimental optimization of DMT-based visible light communication under lighting constraints," *EURASIP J Wirel Commun Netw*, vol. 2020, no. 1, Dec. 2020, doi: 10.1186/s13638-020-01701-9.

[39] R. Rajalakshmi, S. Pothiraj, M. Mahdal, and M. Elangovan, "Adaptive Fuzzy Logic Deep-Learning Equalizer for Mitigating Linear and Nonlinear Distortions in Underwater Visible Light Communication Systems," *Sensors*, vol. 23, no. 12, Jun. 2023, doi: 10.3390/s23125418.

[40] B. Taha, H. A. Fayed, M. H. Aly, and M. Mahmoud, "A reduced PAPR hybrid OFDM visible light communication system," *Opt Quantum Electron*, vol. 54, no. 12, Dec. 2022, doi: 10.1007/s11082-022-04219-0.

[41] L. Bravo Alvarez, S. Montejo-Sánchez, L. Rodríguez-López, C. Azurdia-Meza, and G. Saavedra, "A Review of Hybrid VLC/RF Networks: Features, Applications, and Future Directions," *Sensors*, vol. 23, no. 17. Multidisciplinary Digital Publishing Institute (MDPI), Sep. 01, 2023. doi: 10.3390/s23177545.

[42] F. J. Escribano, J. Sáez-Landete, and A. Wagemakers, "Optimisation of chaos-based coded modulations for compensation of amplifier non-linearities," *Electron Lett*, vol. 52, no. 22, pp. 1855–1857, Oct. 2016, doi: 10.1049/el.2016.2864.

[43] L. Zhang *et al.*, "Kernel mapping for mitigating nonlinear impairments in optical short-reach communications," *Opt Express*, vol. 27, no. 21, p. 29567, Oct. 2019, doi: 10.1364/oe.27.029567.

[44] B. Lin, Z. Ghassemlooy, J. Xu, Q. Lai, X. Shen, and X. Tang, "Experimental Demonstration of Compressive Sensing-Based Channel Estimation for MIMO-OFDM VLC," *IEEE Wireless Communications Letters*, vol. 9, no. 7, pp. 1027–1030, Jul. 2020, doi: 10.1109/LWC.2020.2979177.

[45] X. Liu, J. Zhou, N. Huang, and W. Zhang, "Improved Receivers for Optical Wireless OFDM: An Information Theoretic Perspective," *IEEE Transactions on Communications*, vol. 70, no. 7, pp. 4439–4453, Jan. 2022, [Online]. Available: http://arxiv.org/abs/2201.06995