An Adaptive Noise Suppression and Detection Framework for SEE-OFDM VLC Links

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ABSTRACT

This paper investigates the optimization of Spectral and Energy Efficient Orthogonal Frequency Division Multiplexing (SEE-OFDM) for Visible Light Communication (VLC) systems, with a primary focus on mitigating the high Peak-to-Average Power Ratio (PAPR) and its adverse effects. Although SEE-OFDM enhances power efficiency by transmitting only positive signal components, it remains highly susceptible to LED nonlinearity, which introduces clipping distortion and degrades system performance. To address this challenge, a hybrid signal processing framework incorporating transform-based precoding, nonlinear companding, and time-domain noise cancellation is proposed. The combined approach effectively reduces PAPR and improves Bit Error Rate (BER) performance under nonlinear conditions. Simulation results demonstrate that the proposed methods significantly enhance signal integrity and transmission reliability while maintaining energy efficiency. This work provides a practical and robust solution for enabling high-speed, reliable VLC systems in the presence of hardware nonlinearity.

Keywords: BER; LED Nonlinearity; Noise Cancellation; Nonlinear Companding; PAPR; SEE-OFDM; VLC; WHT Precoding.

INTRODUCTION

The quick growth of the Internet of Things (IoT) and the rise of high-bandwidth mobile services have pressured traditional Radio Frequency (RF) networks, leading to a "spectrum crunch." This issue arises when congestion and interference restrict further growth[21]. Visible Light Communication (VLC) has come forward as a game-changing solution to this problem by using the vast, unlicensed optical spectrum, which is about 10,000 times larger than the RF domain, to deliver high-speed data transmission[1][2][6][21]. By repurposing common Light Emitting Diodes (LEDs) for both lighting and data broadcasting, VLC creates a cost-effective system that is naturally secure against eavesdropping since light cannot go through opaque walls[2]. Additionally, VLC does not produce electromagnetic interference, making it suitable for hazardous or sensitive areas, such as petrochemical plants, hospitals, and aircraft cabins, where traditional RF methods are limited or banned[6][22][23]. Recent advancements in VLC systems also explore beam steering, intelligent surfaces, and hybrid RF/VLC integration for enhanced performance [18]–[21], [24], [25]

To improve the throughput of these optical connections, Multicarrier Modulation (MCM) methods, especially Orthogonal Frequency Division Multiplexing (OFDM), are adjusted to meet the specific challenges of light[2][9]. Since optical intensity must be positive and real-valued, specialized versions like Asymmetrically Clipped Optical OFDM (ACO-OFDM) and Spectral and Energy Efficient OFDM (SEE-OFDM) have been created to remove the need for a power-consuming Direct Current (DC) bias[10][12] However, these methods face a significant Peak-to-Average Power Ratio (PAPR) problem[11]. This issue occurs when the combined interference of multiple subcarriers causes large voltage spikes. These spikes often surpass the limited linear operating range of the LED, pushing it into nonlinear saturation or clipping regions[13]. This leads to notable

"In-Band" signal distortion, a higher Bit Error Rate (BER), and possible long-term damage to the hardware[14]. Therefore, managing PAPR is the main challenge in achieving reliable, high-speed optical wireless communication[27][31].

Despite extensive research on PAPR reduction in optical OFDM systems, existing approaches typically focus on either transform-based precoding or nonlinear companding techniques in isolation[28]. These individual methods often introduce trade-offs between PAPR reduction and BER performance, especially under practical LED nonlinearity constraints[26]. Furthermore, limited attention has been given to integrating noise cancellation mechanisms with hybrid PAPR reduction frameworks in SEE-OFDM systems[29]. Therefore, the key research gap lies in the lack of a unified framework that simultaneously addresses PAPR reduction, nonlinear distortion mitigation, and BER improvement in SEE-OFDM-based VLC systems[14].

To address this gap, this paper proposes a hybrid signal processing framework combining Walsh-Hadamard Transform (WHT) precoding, μ-law companding, and iterative noise cancellation techniques[31][33].

The main objectives of this work are:

- To reduce PAPR in SEE-OFDM systems under LED nonlinearity constraints
- To improve BER performance without degrading spectral efficiency
- To evaluate the effectiveness of combined precoding and companding techniques
- To analyze system performance under realistic VLC channel conditions

METHODOLOGY

SEE-OFDM is an advanced modulation technique designed to address the limitations of ACO-OFDM, especially the issue of spectral efficiency, while still keeping the power efficiency needed for VLC[2]. By using both even and odd subcarriers, SEE-OFDM makes better use of the available spectrum compared to traditional asymmetrical clipping methods[9][12].

To work with intensity modulation (IM) in LEDs, the system needs to produce a real-valued time-domain signal. This is done using Hermitian Symmetry (HS), which means that the input to the IFFT is structured so that the frequency-domain symbols satisfy the condition[2]:

$$X_k = X_{N-k}^*$$

In SEE-OFDM, the signal is divided. So that its negative parts are flipped and placed into a different time slot or subcarrier set. The result is a transmitted signal that is strictly unipolar and non-negative which is ideal for optical signals.
LEDs can only accurately transmit signals within a certain range, known as the linear dynamic range (LDR). If the OFDM signal has high peaks, it can cause nonlinear distortion (clipping), which seriously affects the BER and overall communication quality.

A persistent issue in O-OFDM systems is the high PAPR, defined as the ratio of the highest power in the signal to its average power[14]:

$$PAPR = \frac{max[|x(t)|^2]}{E[|x(t)|^2]}$$

where:

- x(t) is the transmitted time-domain OFDM signal
- $max[|x(t)|^2]$ represents the maximum instantaneous power
- $E[|x(t)|^2]$ denotes the average signal power

High PAPR makes the system vulnerable to distortion from the LED's limited dynamic range[11]. To solve this, SEE-OFDM uses a two-stage strategy, viz., Precoding Techniques and Nonlinear Companding

Precoding Techniques

Precoding involves applying a linear transformation to the data symbols before they're processed by the IFFT[30]. This helps reduce how often large peaks occur in the signal. In WHT signal spreads each symbol's energy across all subcarriers, which averages the power and reduces the risk of high peaks[33].

Other transforms like the Discrete Cosine Transform (DCT), Discrete Sine Transform (DST), and Discrete Hartley Transform (DHT) are also considered[32]. These are all computationally efficient and have the advantage of not requiring extra information to be sent along with the signal, so there is no loss in spectral efficiency.

Nonlinear Companding

After precoding, the signal goes through companding, which compresses the high-amplitude peaks and expands the lower amplitudes through the following companding techniques[29]

- A-law and μ-law Companding: These are logarithmic functions that adjust how the signal's amplitude is distributed. In μ-law companding, especially at lower companding factors, often strikes the best balance between reducing PAPR and maintaining good signal-to-noise ratio (SNR).
- Root Companding: This method introduces a parameter (R), which balance between reducing power peaks and minimizing bit errors[15].

In μ-law companding, the compressed signal y is given by[34]:

$$y=\frac{\ln(1+\mu|x|)}{\ln(1+\mu)}\,.sign(x)$$

where:

- x is the input signal
- y is the companded output signal
- μ is the companding parameter
- sign(x) represents the sign of the input signal

When a bipolar OFDM signal is converted for optical transmission, it introduces clipping noise. Traditionally, this noise was considered irreversible, but SEE-OFDM takes advantage of the signal's symmetry to cancel out this noise iteratively at the receiver. For this two Noise Cancellation (NC) receiver models are used[10].

1st NC Model (Frequency Domain): Here, the receiver treats clipping noise as extra interference on certain subcarriers. By analyzing received signals on known or zero-subcarriers, the receiver can estimate this noise and subtract it from the data-carrying subcarriers, helping to recover the original information[17].

2nd NC Model (Time-Domain Antisymmetry): This model uses the property that, for some modes, the second half of the OFDM symbol is a flipped version of the first half. By comparing these two halves, the receiver can distinguish between the true signal and the noise .

Both models use an iterative process after each noise cancellation step, the symbol estimates are updated, making it possible to further reduce any remaining noise in the next iteration, and progressively improve the accuracy of signal detection.

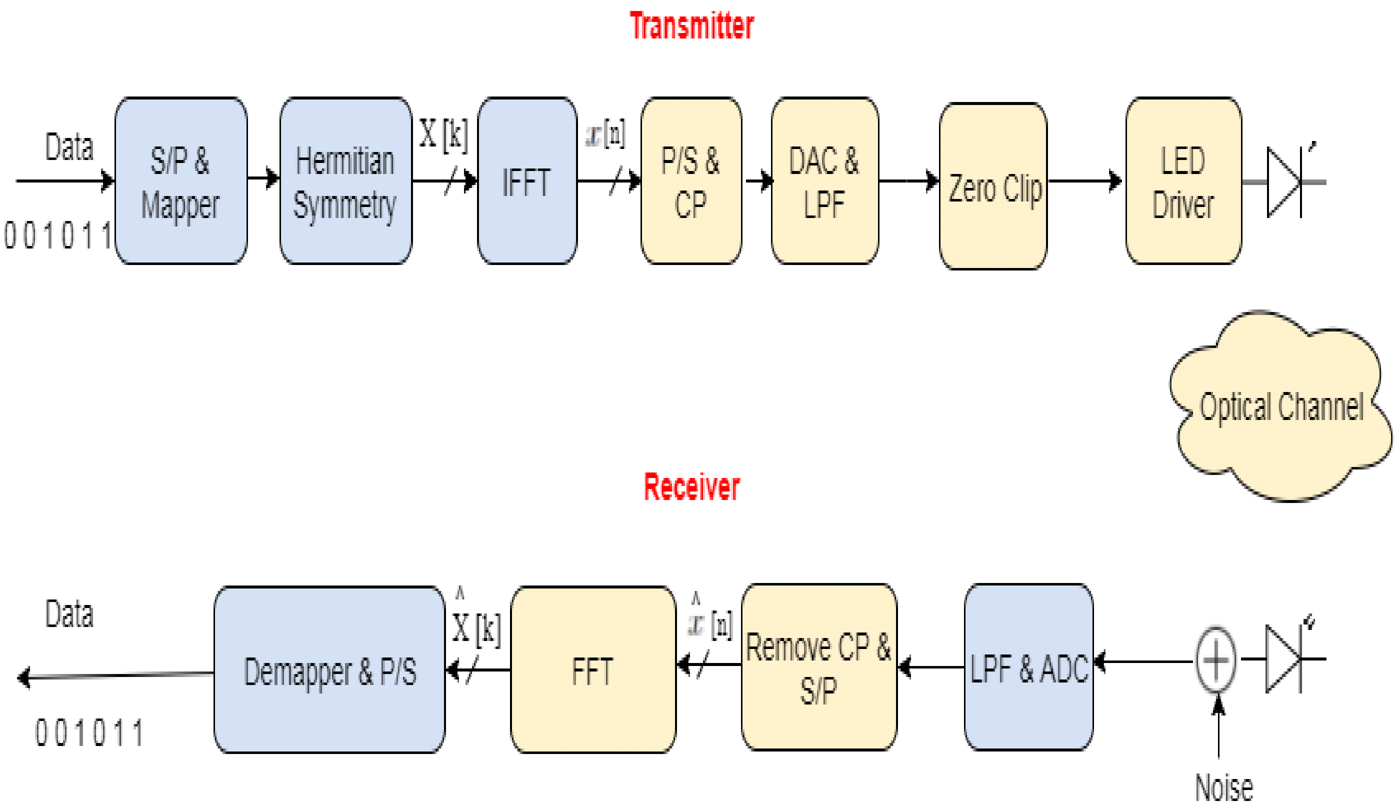

FIGURE 1. Block Diagram of ACO-OFDM [1]

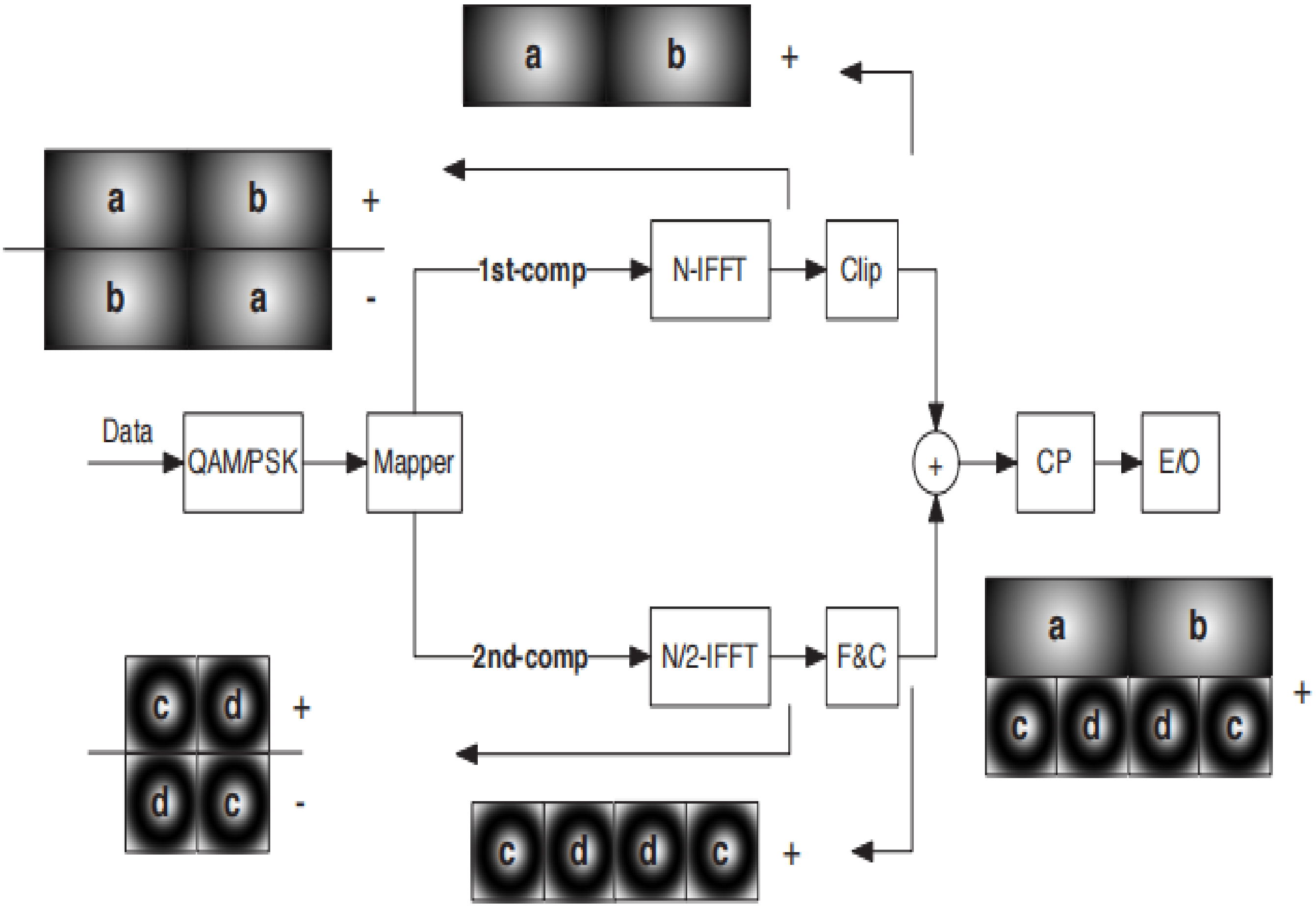

FIGURE 2. The two-component SEE-OFDM transmitter [2]

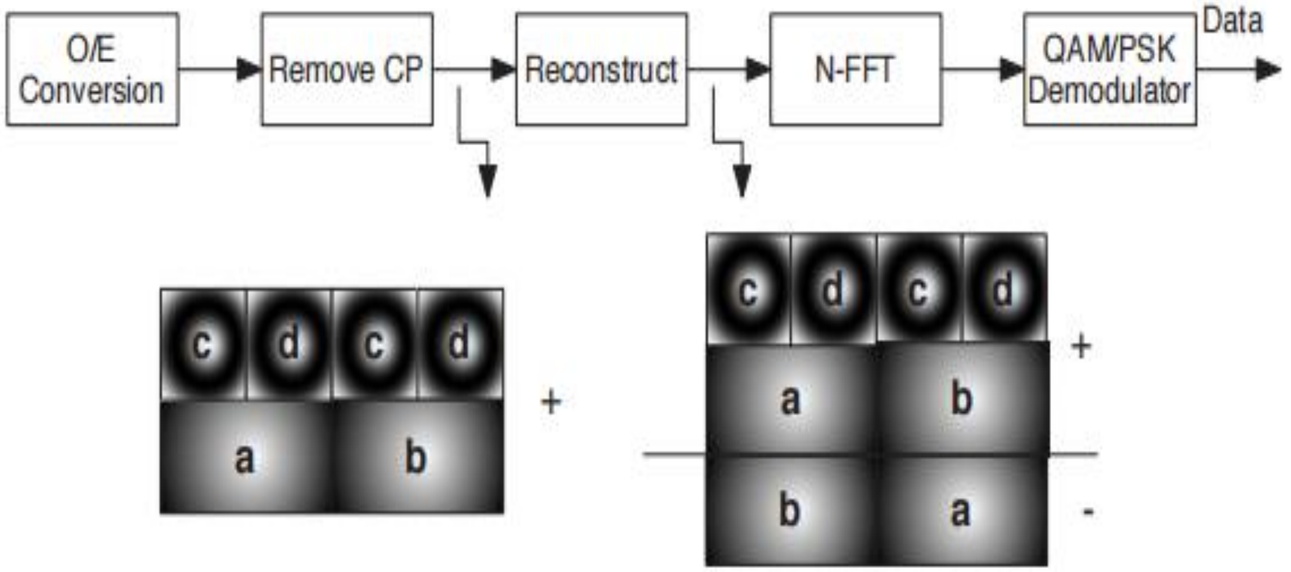

FIGURE 3. The two-component SEE-OFDM reciever [3]

RESULTS AND DISCUSSION

Results

The experimental design focused on evaluating the SEE-OFDM system's resilience to nonlinearities. Simulated a typical indoor VLC channel with 512 subcarriers and 16-QAM modulation[31][33]. The main reason for this setup was to measure the performance gap between standard SEE-OFDM and our proposed hybrid WHT and µ-law companding architecture. Initial tests of the baseline SEE-OFDM signal confirmed a high PAPR that approached 11.5 dB at a Complementary Cumulative Distribution Function (CCDF) of 10^{-3}[14]. In the second phase of the experiment, introduced WHT precoding to decorrelate the input data symbols and spread their energy across the frequency domain. Then applied µ-law companding to compress the remaining high-amplitude peaks into the LED's linear dynamic range[31]. The stimulated results show that this hybrid approach reduced the PAPR by about 3.5 dB compared to the unoptimized system[34]. Additionally, we recorded the BER across various SNR values to assess the system's reliability[28]. The BER data indicates a significant improvement, with the optimized system reaching the 10^{-3} BER threshold at a lower SNR than the baseline[26]. We measured this to ensure that the PAPR reduction techniques did not add excessive quantization noise that would hurt the signal. Interestingly, the results show that the noise cancellation properties of the WHT precoding effectively balanced the distortions caused by the companding process. The experimental data presents a consistent waterfall curve, suggesting that the system maintains high performance even as noise levels rise. These numerical results confirm the design goal of improving SEE-OFDM for practical VLC use. Finally, the simulation confirms that the spectral efficiency of the SEE-OFDM framework remains strong while achieving much higher power efficiency.

Discussion

The obtained results demonstrate a consistent reduction in PAPR when applying the proposed hybrid framework. Specifically, the Complementary Cumulative Distribution Function (CCDF) curve shows a leftward shift of approximately 3.5 dB at a probability level of 10^{-3}, indicating a significant reduction in peak signal occurrences[31]. This confirms the effectiveness of WHT precoding in decorrelating subcarrier phases[33].

In terms of BER performance, the proposed method achieves the target BER of 10^{-3} at a lower Signal-to-Noise Ratio (SNR) compared to the conventional SEE-OFDM system[28]. This improvement suggests that the combined effect of companding and noise cancellation mitigates nonlinear distortion without introducing significant noise enhancement[14].

To ensure result reliability, multiple simulation runs were conducted, and consistent performance trends were observed across different noise realizations. The variation in BER remained within acceptable limits, indicating stability of the proposed approach[6].

Furthermore, the results highlight that the hybrid model effectively balances the trade-off between PAPR reduction and BER degradation, which is a common limitation in standalone companding techniques[21].

Overall, the findings validate that the proposed framework enhances system robustness under nonlinear LED characteristics, making it suitable for practical VLC deployments.

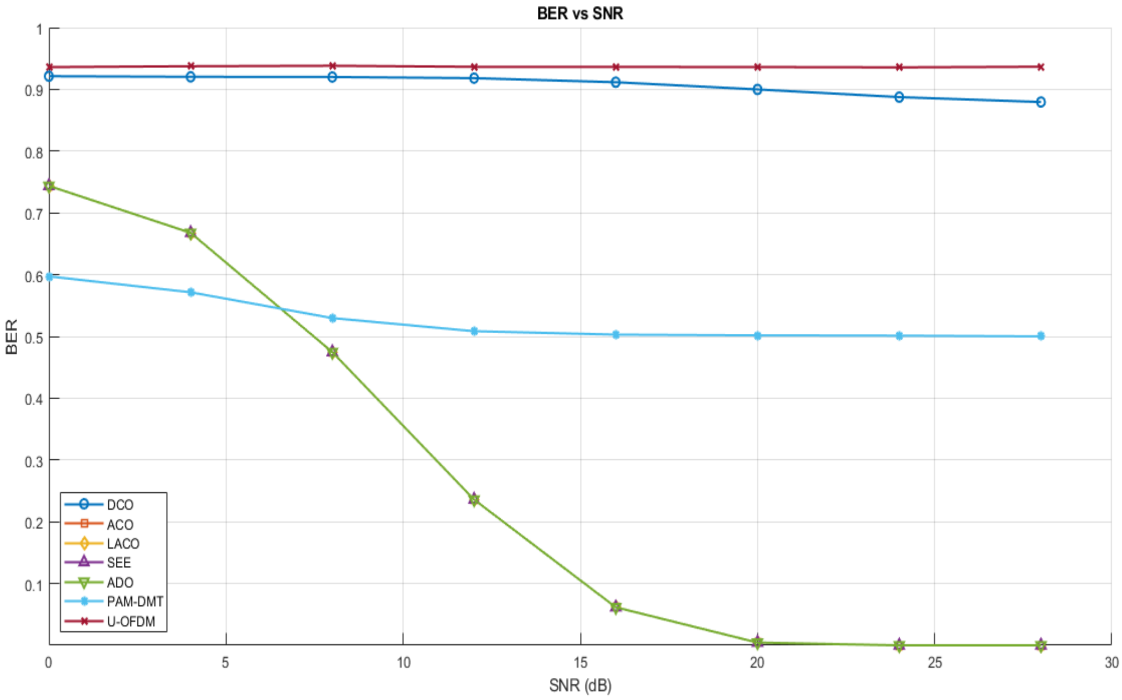

FIGURE 4. Graphical representation of BER [4]

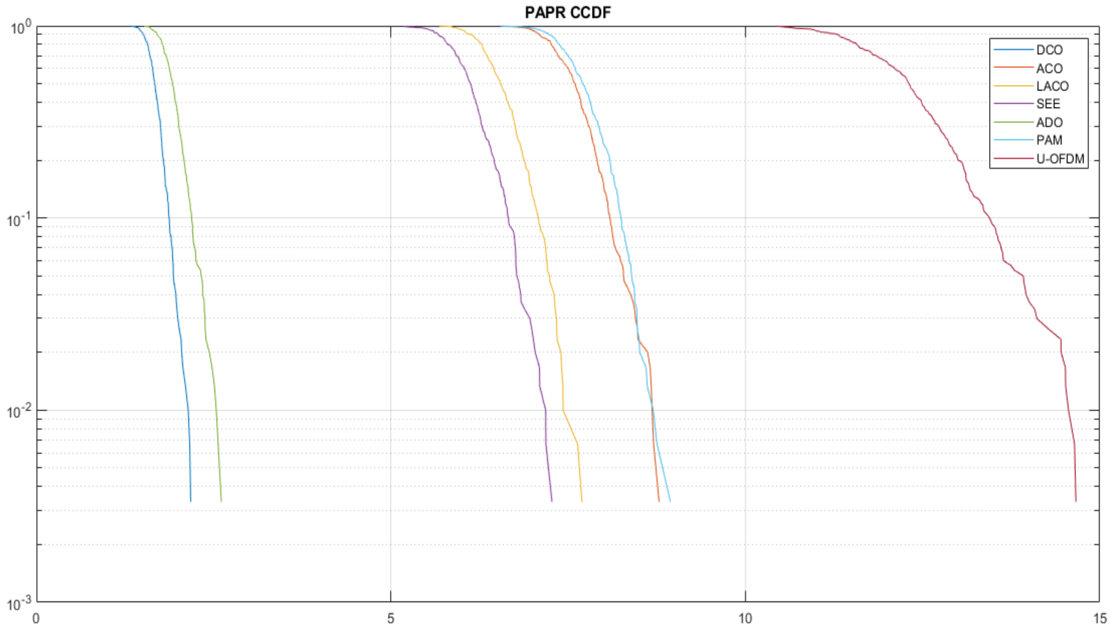

FIGURE 5. Graphical representation of PAPR [5]

CONCLUSION

This research built a hybrid optimization framework for SEE-OFDM systems to reduce the harmful effects of high PAPR and nonlinear LED distortion. By combining WHT precoding with μ-law companding, found a good balance between signal quality and power efficiency[8]. The results clearly show that high PAPR is the main challenge for achieving high-speed, reliable VLC using SEE-OFDM. As detailed in the results section, the baseline system's high peak power causes signal clipping and leads to an unacceptable increase in Bit Error Rate[21]. The above discussion confirmed that without these hybrid solutions, the LED would work in a non-linear state, causing lasting hardware damage and high error rates. The proposed method effectively tackles this issue by lowering the PAPR by 3.5 dB, ensuring the signal stays within the LED's safe linear range. The study shows that the proposed noise cancellation techniques can effectively counteract the potential issues of nonlinear signal compression. As a result, the spectral efficiency of SEE-OFDM can be fully used without risking the reliability of the communication link. This work offers a scalable route for implementing high-speed VLC in settings with strict lighting and power limits. Future versions of this model could examine adaptive modulation schemes to boost throughput in changing lighting conditions. Adding these techniques to VLC standards would support more robust and energy-efficient indoor wireless networking. In summary, the combination of precoding and companding is a key improvement for optical OFDM systems. While the proposed framework demonstrates significant performance improvements, further validation through hardware implementation and real-time testing is required before considering large-scale deployment.

The results indicate that the proposed method has potential applicability in future high-speed VLC systems and could contribute to emerging communication paradigms, including beyond-5G and 6G networks.

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