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Review of transform techniques in optical OFDM systems in terms of PAPR reduction

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Abstract
This review paper offers a comprehensive analysis of various transformation techniques utilized in Optical Orthogonal Frequency Division Multiplexing (O-OFDM) systems, with a particular focus on their implementation in Optical Wireless Communication (OWC), especially in Visible Light Communication (VLC). We examine traditional OFDM methodologies, including Direct Current Biased Optical (DCO-OFDM) and Asymmetrically Clipped Optical (ACO-OFDM). We analyze the mathematical principles associated with these notions, focusing on the Discrete Fourier Transform (DFT), the Real Discrete Fourier Transform (RDFT), and other transforms, including the Walsh-Hadamard Transform (WHT) and the Discrete Hartley Transform (DHT), as well as their applications. We analyze critical concerns inside systems, including the Peak-to-Average Power Ratio (PAPR), and investigate alternate solutions such as selective mapping, partial transmit sequence, tone reserve, and pre-coding techniques. A thorough analysis of current research from 2019 to 2025 is undertaken, highlighting significant advancements, comparative evaluations, and the merits and drawbacks of each methodology. Ultimately, emerging concepts and trends for future research on O-OFDM systems are examined, focusing on computational complexity, power efficiency, spectrum efficiency, and signal integrity.

Keywords: DFT, DHT, OFDM, O-OFDM, OWC, PAPR reduction, RDFT, transform techniques, WHT, VLC

1. Introduction

Frequency Division Multiplexing (FDM) emerged in the 1870s as pioneers such as Bell, Grey, and Edison endeavored to transmit numerous telegraph channels simultaneously. The two primary issues faced by FDM were ineffective frequency spectrum use caused by the guard bands necessary to prevent inter-carrier interference (ICI) and the complexity of the system due to the requirement for separate modulators and demodulators for each subchannel. In 1966, Robert W. Chang established the foundation for OFDM by presenting the idea of non-interfering, overlapping frequencies. In 1980, Peled and Ruiz created the cyclic prefix. To combat ISI, the concept proposed by Weinstein and Ebert, originating in 1971, facilitated effective signal production through the DFT. Initially created in the mid-1980s, functional OFDM systems have proven indispensable in wireless and optical communications. They are essential to multiple technologies, including LTE, Wi-MAX, WLAN (802.11 a/g/n), and 5G networking. Orthogonal Frequency Division Multiplexing (OFDM) is presently the focus of significant research for Visible Light Communication (VLC) applications, attaining data speeds beyond 40 Mbps [1].

2. OFDM Technology

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique utilized in many wireless and wired communication systems to achieve high data rate transmission across flat fading frequency-selective channels. As illustrated in Figure (1), OFDM facilitates the mapping of a substantial quantity of bits from the data stream into a reduced amount of bits across fewer sub-streams. The two streams are sent simultaneously across the identical time-frequency grid via narrow-band subcarriers that are time-orthogonal and frequency-overlapping [2]. DFT and its inverse, IDFT, are utilized to produce frequency and time-domain OFDM signals, respectively efficiently.

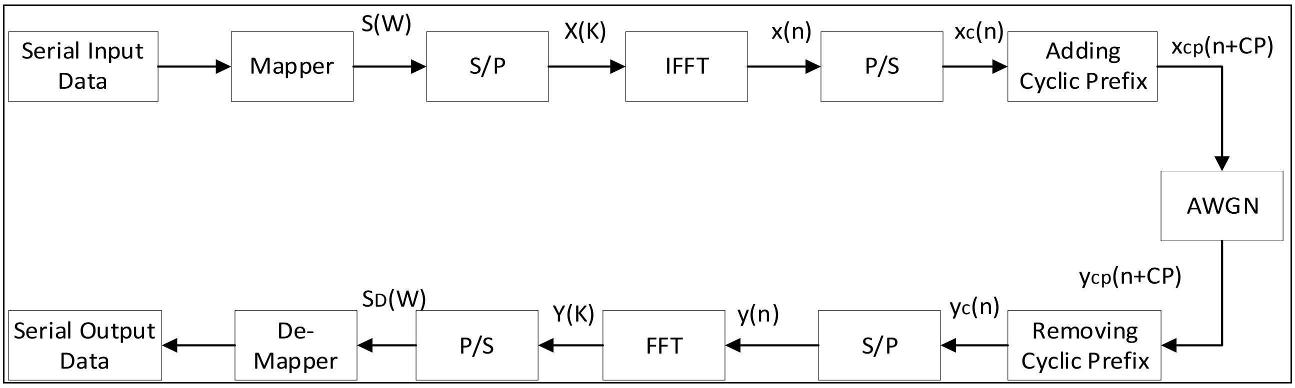

Fig 1: Conventional OFDM block diagram

The DFT of a sampled signal $x[n]$, where n=0, 1,…, N−1, is given by

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j2\pi kn/N}, k = 0,1, \ldots, N-1, \quad (1)$$

Using the inverse transform

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j2\pi kn/N}, \quad (2)$$

This implementation simplifies the system by utilizing a singular IDFT/DFT processor rather than many sinusoidal oscillators [3].

OFDM mitigates multipath fading and inter-symbol interference (ISI) by extending the signal duration and incorporating a cyclic prefix (guard interval). This preserves the orthogonality of the channels and transforms a frequency-selective channel into multiple flat-fading narrow-band channels. OFDM has numerous advantages:

- **Unaffected by localized fading:** Divides the channel into smaller sub-channels that are less susceptible to frequency-specific fading.
- Utilizing substantial bandwidth in a confined area is achievable through overlapping orthogonal subcarriers.
- **Interference resilience:** Narrow-band interference affects just a limited number of subcarriers, hence diminishing the overall damage.
- **ISI resilience:** Symbols exhibit less interaction as their duration is extended and cyclic prefixes are incorporated.
- **Simplified equalization:** Single-tap equalizers are effective due to the narrow-band and flat-fading characteristics of the channels.
- **Potential hardware implementation:** DFT/IDFT techniques provide economical implementations on DSPs and integrated circuits.

Reduced sensitivity to temporal synchronization problems enhances stability in mobile environments

There are several challenges associated with OFDM

- **Elevated PAPR:** This results in RF power amplifiers exhibiting non-linear distortion, hence diminishing their efficiency.
- **Highly susceptible to frequency offset and Doppler shift:** Requires precise synchronization of the carrier frequency.
- **Increased complexity of receivers:** A greater number of subcarriers results in heightened complexity.
- **Computational load:** DFT and IDFT processes necessitate more processing power.
- The cyclic prefix diminishes spectral efficiency, as guard intervals consume bandwidth
- The cyclic prefix diminishes spectral efficiency, as guard intervals consume bandwidth [2-4].

3. Optical Wireless Communications

Optical Wireless Communications (OWC) denotes the transmission of information messages using optical light, devoid of wires, air, or vacuum in the communication pathway. This encompasses technologies such as Free Space Optical (FSO) communication systems, Visible Light Communication (VLC), and Ultraviolet Communication (UVC) systems [5]. Visible Light Communication (VLC) operates within the wavelength range of 390-750 nm and uses Light Emitting Diodes (LEDs) for lighting and data transmission. LEDs are light-emitting devices characterized by rapid response times, energy efficiency, and longevity, rendering them appropriate for various applications in visible light communication, including wireless local area networks, vehicular networks, and wireless personal area networks. Free-space optical (FSO) systems utilize the near-infrared spectral range (750-1600 nm) to provide point-to-point communications. They can transfer data at speeds of up to 10 Gbps, rendering them appropriate for backhauling. UVC, specifically in the solar-blind UV range (200-280 nm), presently has no commercial or military applications. Nonetheless, it presents potential as an alternate wireless communication technique. Its features encompass benefits for wireless sensor networks and ad-hoc networks, chiefly because of its independence from a line-of-sight (LoS) connection [6].

OWC's history extends to antiquity, where individuals employed smoke signals and beacons for visual communication [7]. The photophone was devised in 1880 by Alexander Graham Bell. It utilized solar energy to transmit speech across a distance of two hundred meters. This signifies a substantial progression. Despite the lack of commercialization of photophone technology, it served as a foundation for further developments in optical communication. The invention of lasers in the mid-20th century significantly impacted optical communication technologies. Experimental ultralong-haul optical communication lines commenced in the 1960s. Most of the existing OWC research is relevant solely to military and aerospace contexts. Nonetheless, it has been garnering renewed interest in recent years due to developments in

VLC, FSO, and UVC methodologies [7].

OWC systems provide an alternative to conventional radio-frequency (RF) wireless systems, which are currently encumbered by spectrum congestion and increasing demand for high-capacity communication [6]. The rising prevalence of smart devices is driving an increased need for data transfer, making OWC technologies, such as VLC, essential for widespread wireless communication with reduced energy usage. VLC systems utilize the unlicensed visible light spectrum, spanning 380-750 nm, providing substantial bandwidth for rapid data transmission. LEDs possess the capability to switch on and off rapidly, enabling simultaneous illumination and communication. Consequently, they are applicable for indoor networking, Internet of Things, underwater communications, and high-security situations. The implementation of VLC Systems for data transfer may offer benefits in energy conservation and cost reduction by utilizing the existing lighting infrastructure [7].

OWC systems, particularly VLC, possess intrinsic advantages over RF systems regarding data speeds and security, rendering them suitable for various applications. Systems founded on this idea exhibit greater immunity to external interferences compared to RF transmission. They possess the ability to facilitate both illumination and communication, representing a significant advancement in wireless communication [6] [7]. Given the continuous progress of VLC technologies, especially regarding data rates and system performance, their incorporation into next-generation wireless networks seems increasingly likely, particularly for applications necessitating high-speed backhaul or dense indoor wireless communication [6].

4. Visible Light Communication

The swift progress of communication technologies and the growing need for high-speed wireless applications, including Virtual Reality (VR), Augmented Reality (AR), the Internet of Things (IoT), autonomous vehicles, telemedicine, and Artificial Intelligence (AI), have prompted apprehensions about the capability of current radio frequency (RF) communication systems to satisfy these new demands [1]. The rising prevalence of mobile devices necessitates alternate methods to manage the escalating data requirements, particularly when spectrum constraints are anticipated by 2035. RF systems are extensively disseminated yet encounter issues related to interference, restricted bandwidth, and security vulnerabilities. This has prompted the exploration of millimeter-wave communication and visible light communication. VLC systems operate within the wavelength range of 380-780 nm and transmit data using optical sources such as LEDs and Laser Diodes (LDs). It serves as an alternative to RF systems, offering a more stable and robust technology that utilizes an unlicensed spectrum without incurring usage costs. It also ensures security: light cannot penetrate walls and other surfaces impervious to optical transmission, hence guaranteeing communication privacy [1] [8]. VLC systems are resistant to electromagnetic interference, making them suitable for environments such as hospitals and airplanes where RF communication is typically restricted [1].

The origins of visible light communication can be traced back to the utilization of smoke and fire signals in ancient times. These methods developed progressively, culminating in the semaphore in the late 18th century [9]. Alexander Graham Bell's photophone, developed in 1880, was a significant advancement. Its voice transmissions were conveyed using beams of light, establishing it as the world's inaugural communication system utilizing light. Despite the constraints imposed by contemporary technology, it established a foundation for further advancements in optical communication [9]. VLC underwent substantial progress in the 20th century, notably with the introduction of LEDs, facilitating data transfer via light. The growing interest in VLC is primarily due to the advancement of solid-state lighting technologies, especially high-efficiency LEDs [1]. LEDs exceed conventional incandescent lamps in durability, energy efficiency, and temperature performance. This makes them appropriate for use in both illumination and communication [1, 9].

Recent developments in VLC systems have achieved data speeds of many gigabits per second. Li-Fi (Light Fidelity) systems, which employ LED-based illumination for data transmission, have exhibited considerable potential. Data transmission rates may surpass 1 Gbit/s, with the possibility of achieving greater speeds via sophisticated modulation techniques like Orthogonal Frequency Division Multiplexing (OFDM) and Carrier-less Amplitude and Phase (CAP) [8]. These technologies will be essential in the advancement of future wireless communication standards, including 5G and 6G. They will employ RF technology to deliver swift, secure, and interference-free communication solutions [1, 8]. These technologies will be essential in the advancement of future wireless communication standards, including 5G and 6G. They will employ RF technology to deliver swift, secure, and interference-free communication solutions [1, 8]. International research on VLC is proliferating. Academia and business are diligently tackling issues associated with modulation bandwidth, signal-to-noise ratios (SNR), and system integration to actualize the full potential of VLC in the upcoming generation of wireless communications. The predominant techniques in VLC-based O-OFDM are DCO-OFDM and ACO-OFDM, which are elaborated upon below:

4.1 Direct Current Biased Optical-OFDM

DCO-OFDM is a simple and spectrally efficient optical OFDM technique commonly employed in VLC [10]. As shown in Figure 2, the transmitter initially utilizes modulation techniques such as M-PSK or M-QAM to transform serial input data bits into complex modulated symbols. These are additionally categorized into Hermitian symmetry (HS), converted from serial to parallel, and processed by the IDFT to yield a real-valued time-domain signal [10][1]. Hermitian symmetry ensures that the frequency domain signal $X(k)$ follows the requirement $X(k) = X^*(N-k)$, with $X(0) = X(N/2) = 0$, hence ensuring a real output after the IDFT [1][11]. This procedure may be expressed numerically as:

$$X_H = [0, X(0), X(1), \dots, X(N/2-1), 0, X^*(N/2-1), \dots, X^*(0)] \quad (3)$$

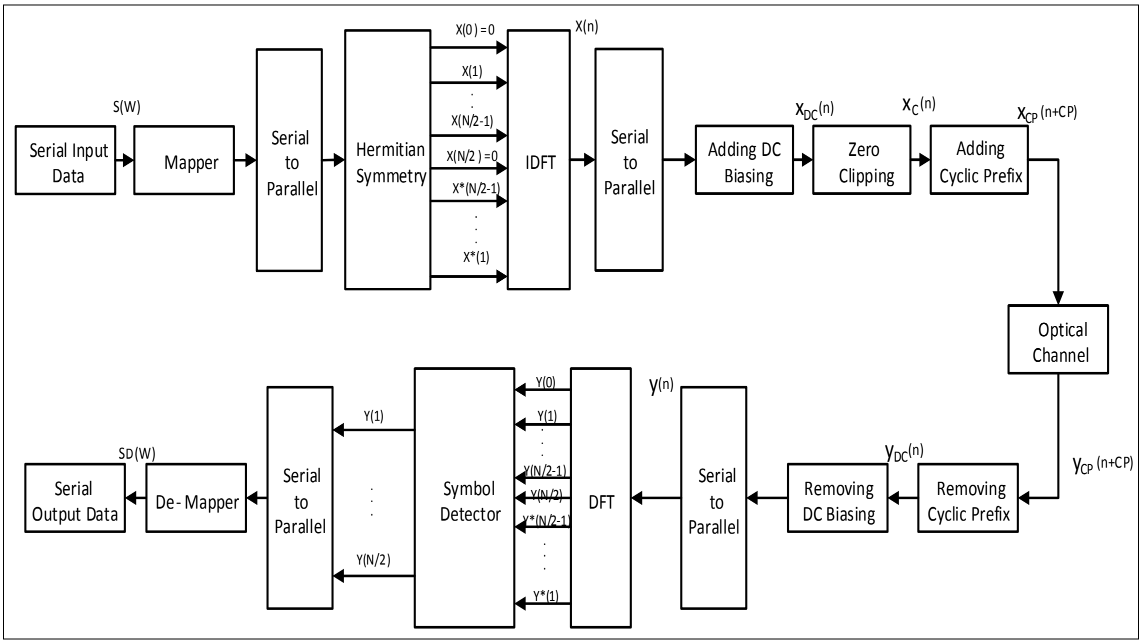

Fig 2: Conventional DCO-OFDM (DFT-based) block diagram

Utilizing the IDFT, the resultant time-domain signal is as follows

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_H(k) e^{j\frac{2\pi nk}{N}}, \quad (4)$$

$X_H(k)$ Represents the k-th subcarrier, and N signifies the total number of subcarriers.

Negative peaks are truncated to guarantee compatibility with optical transmitters; therefore, applying an adequate DC offset to the generated real bipolar signals yields positive, unipolar signals suitable for optical transmission. The DC offset, referred to as DC_{bias}, is crucial for mitigating clipping noise.

$$DC_{bias} = \eta\sqrt{E\{|x(t)|^2\}}, \quad (5)$$

Where $E\{|x(t)|^2\}$ is the electrical power and is calculated using $10\log_{10}(\eta^2 + 1)\ dB$, where η represents a proportionality constant, clipping the signal produces clipping noise, which must be regulated by selecting suitable DC bias levels; a lower bias results in more clipping noise, hence affecting system performance [10, 12].

Subsequently processed and expanded with a cyclic prefix (CP), the time-domain signals mitigate inter-symbol interference (ISI). Through digital-to-analog conversion (DAC), the signal is modified for LED transmission in the optical channel [13, 11].

A photodiode (PD) converts the optical signal into an electrical signal at the receiver, which is further amplified by a trans-impedance amplifier and processed by analog-to-digital conversion (ADC). The signal undergoes the DFT to retrieve the original frequency-domain symbols after the elimination of the cyclic prefix. Serial conversion and

Even with challenges such as elevated peak-to-average power ratio (PAPR) and optical energy inefficiencies arising from DC biasing [12, 11], this whole process maintains spectrum efficiency and simplicity, making DCO-OFDM a prevalent method in optical wireless communications.

4.2 Asymmetrically Clipped Optical-OFDM

The DFT of a sequence $x(n)$ of N length is defined in Equation (2-1), where $X(k)$ and $x(n)$ in the DFT denote complex signals, including phase and amplitude components [14]. ACO-OFDM generates a positive-valued unipolar signal without requiring an additional DC bias, addressing the loss of power in traditional DCO-OFDM systems. As shown in Figure (3), serial input data bits are initially mapped onto complex symbols, such as M-QAM or M-PSK, within the transmitter, followed by conversion into parallel form. Data symbols are transmitted solely on odd-indexed subcarriers, while even subcarriers are maintained at zero to facilitate positive biasing of the signal [1, 12, 13].

Hermitian symmetry ensures that the time-domain signal resulting from the IDFT operation is real and exhibits anti-symmetry properties, expressed as:

$$x(n) = -x\left(n + \frac{N}{2}\right), \quad 0 \le n \le \frac{N}{2} - 1 \quad (6)$$

Allowing negative signal components to be clipped without incurring information loss [1, 12, 10]. The frequency-domain frame structure is expressed as follows:

$$X_H = [0, X(1), 0, X(3), \dots, X(N/2-1), 0, X^*(N/2-1), \dots, X^*(1)] \quad (7)$$

Ensuring that the IDFT produces exclusively a completely real output signal [1, 12, 10].

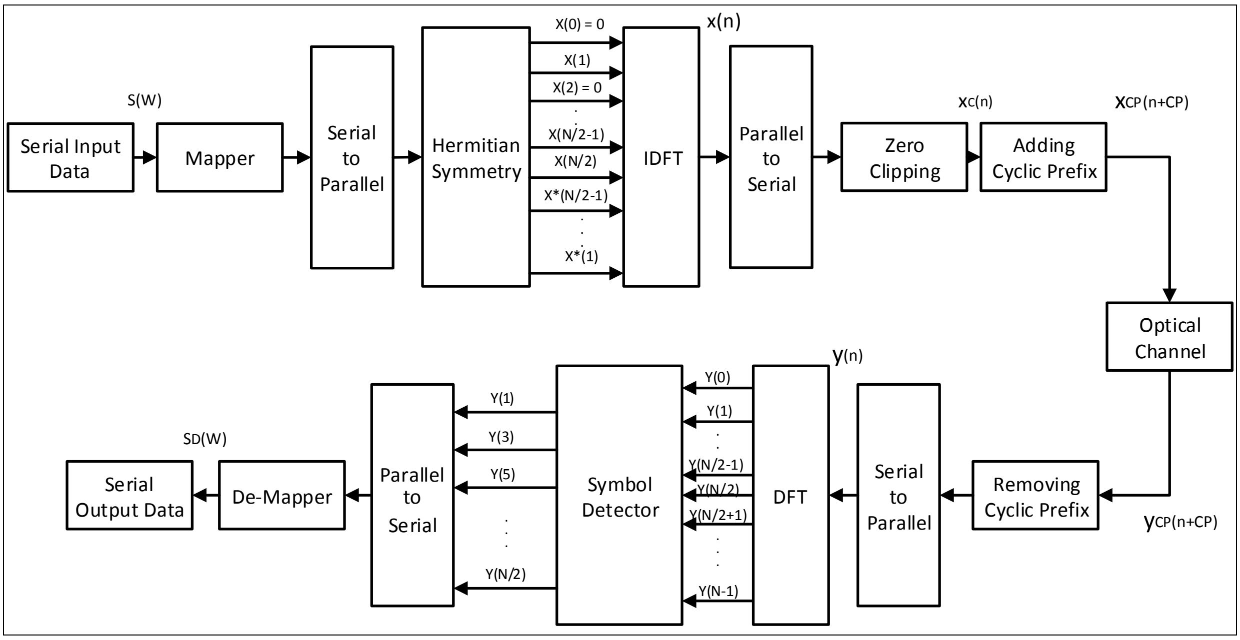

Fig 3: Conventional ACO-OFDM (DFT-based) block diagram

The direct clipping of the negative components of this time-domain signal at zero produces an appropriate unipolar signal for optical transmission, as illustrated:

$$s_{Clipped}(n) = \begin{cases} s(n), s(n) \geq 0 \\ 0, \ s(n) < 0 \end{cases} \quad (8)$$

This clipping maintains the integrity of the transmitted information symbols by introducing noise exclusively in even-indexed subcarriers, which contain no data [12, 10]. The signal undergoes digital-to-analog conversion before transmission through an optical channel utilizing LEDs [1, 13, 15]. A cyclic prefix (CP) is incorporated to mitigate inter-symbol interference (ISI).

A photodiode converts the optical signal into an electrical form at the receiver. After analog-to-digital conversion and cyclic prefix removal, the signal experiences a DFT to revert to the frequency domain. The clipping distortion is observed to be confined to even subcarriers, while the odd subcarriers, which carry the actual data, remain unaffected. As a result, the transmitted data symbols are efficiently recovered through DFT processing, followed by de-mapping and serial conversion to retrieve the original data stream. [1, 10, 15]. ACO-OFDM demonstrates superior power efficiency compared to DCO-OFDM; however, the spectral efficiency experiences an approximate 50% reduction owing to the exclusive transmission of data on odd subcarriers [15].

5. Real Discrete Fourier Transform

The RDFT is a fundamental mathematical method of digital signal processing, especially designed to handle real signals commonly quantified in practice [16]. In the RDFT, all inputs of the sequence $x(n)$ are real, resulting in the output $X(k)$ being conjugate symmetric:

$$X(N-K) = X^*(k), 1 \leq k \leq N/2 - 1 \quad (9)$$

$X(0)$ and X $(N/2)$ represent real output signals, whereas the other outputs exhibit conjugate symmetry. The forward RDFT is defined as [16]:

$$X(k) = \sum_{n=0}^{N-1} x(n) cos\left(\frac{2\pi nk}{N} + \theta(k)\right), \quad (10)$$

$$\text{where } \theta(k) = \begin{cases} 0, & 0 \leq k \leq N/2 \\ \frac{\pi}{2}, & N/2 < k \leq N-1' \end{cases}$$

The inverse RDFT is articulated as follows:

$$x(n) = \frac{2}{N}\sum_{k=0}^{N-1} X(k) v(n) cos\left(\frac{2\pi nk}{N} + \theta(k)\right) \quad (11)$$

$$\text{where } v(n) = \begin{cases} \frac{1}{2}, & n = 0, N/2 \\ 1, & otherwise \end{cases}$$

Where $x(n)$ a real-valued time-domain is signal, and $X(k)$ is a frequency-domain signal [17]. Physical signals are primarily real; the RDFT takes advantage of the conjugate symmetry of the signal and consequently, the number of operations required is almost half that of the traditional complex DFT [18]. In particular, the RDFT outputs have a symmetry, which significantly simplifies computation [19].

The RDFT holds both theoretical importance and practical advantages as the foundation of modern signal processing, offering significant computational advantages and specializing in processing real-valued signals across various applications.

6. Peak-to-Average Power Ratio (PAPR)

The PAPR of an OFDM signal is defined as the ratio of the maximum instantaneous power to its average power:

$$PAPR = \frac{max|x(n)|^2}{E[|x(n)|^2]} \quad (12)$$

Where $x(n)$ is the time-domain OFDM signal after the IDFT, and $E[\cdot]$ denotes expectation [1]. High PAPR arises because an OFDM signal is a summation of many independently modulated subcarriers. When these subcarriers align in phase, the peak power can be much higher than the average power [20]. This causes issues such as:

- Non-linear distortion due to the limited linear range of power amplifiers and LEDs [21, 22, 1].
- Increased BER and out-of-band radiation due to clipping and non-linearities [23].
- Inefficiency in transmitter components like DACs, LEDs, and amplifiers [1].

These issues are bad situations in VLC and Optical OFDM (O-OFDM) systems, where the transmitter (e.g., LED) has a strict linear operating range [21, 24, 22].

6.1 PAPR in Optical and Wireless Domains

In optical communication, particularly with IM/DD (Intensity Modulation / Direct Detection) based OFDM, the Gaussian-like amplitude distribution of the OFDM signal demands a wide linear dynamic range. The non-linearity of LEDs severely impacts performance, making PAPR a critical parameter [21, 24, 22].

Similarly, in wireless OFDM systems, the presence of high PAPR causes significant signal distortion. It leads to an inefficient use of the power amplifier, requiring a power back-off that lowers efficiency [10, 25].

6.2 Mathematical and Statistical Analysis

The statistical behavior of PAPR is often analyzed using the Complementary Cumulative Distribution Function (CCDF):

$$CCDF = P(PAPR > PAPR_0) = 1 - (1 - e^{-PAPR_0})^N \quad (13)$$

This expression assumes N subcarriers and Gaussian-distributed time-domain samples, a condition met by the Central Limit Theorem for large N [10, 1].

6.3 Techniques for PAPR Reduction

A variety of PAPR reduction techniques have been proposed, classified into:

- **Selective Mapping (SLM):** Operates by generating multiple copies of a single signal, each version having a unique phase shift. The transmitter selects the option with the lowest peak power for transmission among the available choices. This method reduces the PAPR by attenuating the peaks in the signal while preserving the original data [26].
- **The Partial Transmit Sequence (PTS):** This method divides the original data block into smaller sub-blocks and applies a phase rotation to each sub-block. The sub-blocks are assembled to minimize the overall peak power of the transmitted signal. PTS achieves a significant reduction in PAPR while ensuring data security through the strategic selection of phase factors [27].
- **Tone Reservation (TR):** Allocates specific subcarriers for peak reduction rather than data transmission. These reserved tones incorporate specific signals that mitigate high peaks in the time-domain signal. TR effectively smooths the signal and reduces PAPR, although at the expense of available bandwidth for data [28].
- **Tone Injection (TI):** Reduces PAPR by intentionally introducing additional signals (tones) beyond the original data constellation points. This "injection" modifies the signal by altering the distribution of power, resulting in a reduction of the prominent peaks. TI modifies the representation of the signal; however, the receiver is still capable of retrieving the data [28].
- **Pre-coding and coding techniques:** Modify the data in specific manners or incorporate error-correcting codes. These methods inherently modify the signal to reduce peak values. A well-designed coding scheme results in a transmitted signal that consumes less power and exhibits reduced likelihood of high peaks. Walsh Hadamard Transform as an example [20, 22, 25, 23]:

6.4 Walsh-Hadamard Transform

The WHT effectively reduces PAPR in OFDM systems. The Hadamard Transform matrix (H) is a square matrix characterized by elements that take values of either 1 or -1; it significantly reduces the autocorrelation of the input data sequence. The Hadamard matrix of order 2 is as follows:

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (14)$$

This approach could reduce the number of signal peaks without requiring additional information from the receiver [29]. This method generates symbol sequences with reduced correlation by aligning the order N of the Hadamard matrix with the number of OFDM subcarriers. This facilitates more effective control of power peaks. Before applying the IDFT, pre-coding techniques enhance the WHT by multiplying frequency-domain modulated data blocks with a specified pre-coding matrix H. In the absence of rate loss considerations, the dimensions of the pre-coding matrix are typically $N \times N$, indicating no penalties associated with data rate [2]. WHT-based pre-coding methods recently introduced in Optical OFDM (OOFDM) systems aim to decrease PAPR by minimizing data autocorrelation. The structured Hadamard matrix facilitates this capability, and the recursive generation method ensures the consistent production of low-correlation output signals, significantly enhancing system performance [30].

7. Literature Review

In 2019, Spandana *et al*. [31] proposed the usage of DHT and WHT to decrease PAPR in OFDM systems. Although a decision tree with WHT is still a good candidate if computational cost does not pose a serious concern, DHT is found to be more efficient in minimizing PAPR over WHT. The results show that DHT-precoding can effectively lower the PAPR with low complexity, making it suitable for optical communication systems that require low hardware cost and power consumption.

In 2020, Mapfumo *et al*. [32] compared DFT and DHT hybrid systems over ACO-OFDM for PLC-VLC systems. The work points out that although each is already better in some respect, its computational complexity reduction ability is weaker than that of the DHT. The lower complexity and higher spectral efficiency are more critical for real-time optical communication systems, which are achieved by a relaxation of the Hermitian symmetry condition present in the DHT. DFT has better noise tolerance, making it also applicable in an impulsive noise environment. Performance presented in this paper shows that DHT-based systems provide better PAPR reduction, which in turn reduces the latter's need for complex hardware implementation in

PAPR-sensitive systems.

In 2021, Hacioglu *et al.* [33] presented the Combining Real and Imaginary Parts (CRIP) algorithm for the design of optical OFDM waveforms. This eliminated the need for Hermitian symmetry by combining the real and imaginary parts of the IDFT result. The CRIP method improves the spectral efficiency and dramatically lowers the computational load. This acts as a practical alternative to energy-efficient, real, positive-valued optical systems in energy-efficient OWC, as it successfully cancels the ISI and diminishes the clipping noise. Although it simplifies the implementation, in some particular cases, it introduces minor errors that affect the BER performance.

NA Mohammed *et al.* [34] proposed in 2021 a technique to mitigate the PAPR in ACO-OFDM systems for VLC via combining Non-Linear Companding Technique (A-law, μ-law) and Pre-coding Technique (WHT, DCT and DHT). The hybrid one could improve the QAM modulations by trading off the BER performance and the PAPR reduction. However, this will make calculations more complex, especially for systems with many subcarriers.

XU *et al.* (2022) [35] suggested combining DHT with an index modulation scheme in optical OFDM systems. Spectral-efficiency improvement in the joint method of DHT and index modulation is due to the transmission of higher data bits for each subcarrier. The results of this investigation indicate that O-OFDM systems based on DHT using index modulation achieve significant BER gains when spectral efficiency is the same compared to DFT-based systems. This proposal guarantees the link quality, simultaneously saving power and reducing the complexity of the algorithm.

In 2022, J Abdulwali and S Boussakta [36] introduced C-OFDM to mitigate the problem of PAPR and LED non-linearity robustness improvement in VLC by using Walsh-Hadamard and DCT techniques. Although conventional DCO-OFDM offered better PAPR and BER performance, it was recommended to be used in PAM as it was not the most suitable for QAM modulation and required a fine-tuning of some of its parameters to achieve a good performance.

The above C-transform was first used in optical OFDM systems in 2023 by Leftah. [37]. This ability of the C-transform to avoid the necessity of Hermitian symmetry in order to obtain real-valued outputs highlights its significant computational advantage concerning the use of the DFT, as compared to a DFT-based system characterized by excellent channel equalization and robustness, the system's spectral efficiency is slightly reduced. In contrast, significant savings in computational complexity are achieved. Because of its high-power efficiency, the C-transform is especially viable for systems with stringent power requirements, such as VLC systems deployed in restricted environments.

Khalaf *et al.* [24] studied the non-linear companding for PAPR reduction based on ACO-OFDM systems in 2023. They demonstrated that non-linear companding can significantly increase PAPR while maintaining BER performance. The paper suggested the use of μ-law companding for real-time VLC systems with low latency and fast processing demands, for the improvement of the performance of the signal with higher computational requirements.

In 2024, Cinemre *et al.* [38] suggested Gaussian pre-coding for PAPR reduction in DCO-OFDM. Although Gaussian pre-coding led to a slight degradation in BER performance, it exhibited better PAPR performance in comparison with the conventional DCT pre-coding methods. In addition, optimization of the trade-off between the PAPR reduction and the corresponding BER is required in VLC systems for power efficiency and signal quality.

Finally, Sanya *et al.* [39] (2025) used the DHT and Real-DFT to investigate low complexity schemes for ACO-OFDM. Their analysis showed that both transforms present similar BER performance, while they could reduce the complexity compared with DFT. DHT is a good compromise between bit error rate and computational complexity, especially for systems with inadequate computation power. The Real-DFT method abstains from increased optimization, but demands phase equalization at the receiver. The previous works of transform techniques in O-OFDM systems are summarized in Table 1.

Table 1: O-OFDM transform techniques related works

Reference	Year	Transform	Advantages	Drawbacks
Spandana *et al.* [35]	2019	DHT, WHAT	Better PAPR reduction (DHT), lower complexity	DHT is not suitable for using higher-order QAM and PSK modulation schemes
Mapfumo & Shongwe [36]	2020	DFT, DHT	Reduced PAPR, improved BER under noise, DHT offers reduced complexity	Limited modulation flexibility, better suited for PSK over QAM
Hacioglu *et al.* [37]	2021	CRIP	Reduced complexity, improved spectral efficiency	Small errors in BER
Mohammed *et al.* [38]	2021	WHT, DCT, DHT, A-law, μ-law	Significant PAPR reduction, efficient balance between PAPR and BER, suitable for QAM	Increased computational complexity with higher subcarriers
Xu *et al.* [39]	2022	DHT, Index Modulation	Improved spectral efficiency, lower power consumption	Higher system complexity
Abdulwali & Boussakta [40]	2022	C-transform (WHT, DCT)	High PAPR reduction, resilient to LED non-linearity, improved BER	Limited performance with QAM requires careful parameter tuning
Leftah *et al.* [41]	2023	C-transform	Lower computational complexity, better power efficiency	Reduced spectral efficiency
Khalaf *et al.* [28]	2023	Non-linear companding	PAPR reduction, minimal BER impact	Increased computational load
Cinemre *et al.* [42]	2024	Gaussian pre-coding	Superior PAPR reduction	Slight BER degradation
Sanya *et al.* [5]	2025	DHT, Real-DFT	Lower computational complexity, comparable BER performance	Decreased spectral efficiency

8. Conclusion

Transform approaches significantly influence the speed and efficiency of O-OFDM systems, particularly with complex mathematical challenges and elevated PAPR. DCO-OFDM and ACO-OFDM remain advantageous due to their effective balancing of power and spectrum efficiency. Recent developments have produced encouraging outcomes, as transformations such as the DHT, WHT, and RDFT facilitate successful PAPR reduction and streamlined deployment; yet, they necessitate various trade-offs concerning complexity and spectral efficiency. Hybrid approaches employing pre-coding and compounding have demonstrated the ability to enhance system performance by optimizing the trade-off among bit error rate (BER), complexity, and power consumption. Future research must focus on creating low-complexity transforms, enhancing modulation techniques, and investigating hybrid tactics to satisfy the growing demand for resilient, energy-efficient, and high-speed optical wireless communication systems. This will facilitate the integration of these technologies with next-generation wireless networks.

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