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Emerging Architectures in Direct-Clip Optical Communication: A Comprehensive Review

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Abstract

The global demand for ultra-high-speed data transmission intensifies, Intensity-Modulation Direct-Detection (IM/DD) systems have recently turned as the pillar of short-reach optical networks like 5G/6G front haul, hyper-scale data-centres and Optical Wireless Communication (OWC/Li-Fi). Out of all the modulation candidates, Direct-Current Biased Optical Orthogonal Frequency Division Multiplexing (DCO-OFDM) is one of the most promising modulation formats due to the benefits of high spectral efficiency and immunity to the multipath fading and ISI due to the inherent nature of this format. Nonetheless, high DC bias currents must be used to prevent signal clipping in optical emitters (e.g., Light Emitting Diodes (LEDs) and Laser Diodes (LDs)) due to the large power fluctuations, which results in inefficient energy utilization and an accelerated deterioration of the component. In addition, if these peaks become larger than the small linear dynamic range of inexpensive hardware then they cause strong non-linear distortion, greatly increasing the Bit Error Rate (BER) while also limiting the modulation order possible (e.g. 64-QAM to 1024-QAM). This review totally examines the Direct Clip framework a further developed type of digital flag handling (DSP) that is utilized to limit these impediments. While typical clipping regards signal peaks as random errors, Direct Clip takes advantage of Iterative Clipping and Filtering (ICF) and Noise Shaping to actively push the signal envelope into the ideal domain of operation for hardware. This paper illustrates the trade-offs between computational complexity, spectral leakage, and fidelity through individual blocks to show how Direct-Clip architectures facilitate the utilization of low-resolution Digital-to-Analog Converters (DACs) and non-linear optical components for high-throughput applications. These findings confirm that Direct-Clip Optical-OFDM is much more than an incremental advance, but rather one of the core building blocks for sustainable, low-cost, high-capacity Optical connectivity at the next level of software-defined networks.

Keywords: DCO-OFDM, Direct-Clip, Optical Wireless Communication (Li-Fi), Non-Linear Distortion Mitigation, and IM/DD Systems.

1. Introduction

The ever-increasing need for high-quality multimedia services has fuelled demand by end users for bandwidth in mobile communications to support broadband wireless services such as high-definition

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TV, mobile videophones, video conferencing, high-speed Internet access, etc. The quest for higher bandwidth will only grow stronger over the next decade [1]. Various technologies used in access networks to serve end users with communication needs are: copper-based, hybrid coaxial and optical fiber cables, fiber-to-the-home, broadband RF/microwave wireless technologies. Extending Bandwidth Copper/Coax/ RF Cellular/Microwave FTTH driven worldwide demand is intensifying, and the inadequacy of copper/coaxial cables and RF cellular/microwave technologies, with very narrow bandwidth, fast saturating spectrum, security issues, high cost of installation and high cost value of accessibility to all, must be apparent. Very soon terrific bandwidth will be available to customers as network operators around the globe begin to deploy optical fiber-based access networks. However, one of the most common myth about these optical fiber based networks is that they provide limitless bandwidth which is not true, because various architectural choices, device and component compatibility issues, and the performance limits of network equipment and system deployment do result in a limited capacity been presented to the end users [2]. Optical wireless communications (OWC) is a fresh technology that innovations last three decades and with high demands to increase the capacity of the countries usage nowadays there is many approach to change the electrical signal to optical signal.

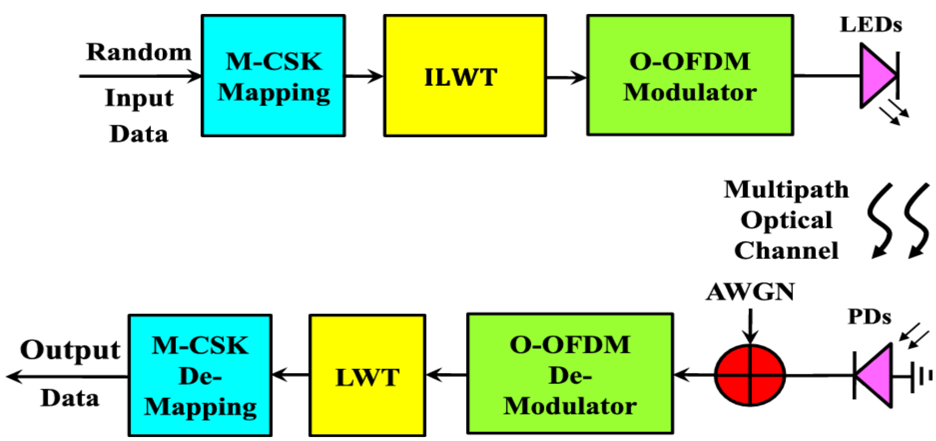

Figure (1): optical -orthogonal frequency division communication (O-OFDM) [3]

2. Intensity Modulation and Direct Detection

Intensity modulation and direct detection (IM/DD) is the combination of the transmitter and receiver. In this paper, an indoor optical wireless communication (OWC) system using transceiver based on IQ modulator and photonic integrated circuit is established and employed in space data communication, while the indoor OWC system always works based on IM/DD due to low cost optical carrier modulation and demodulation. From the desired waveform, the optical carrier instantaneous power is modulated, then the instantaneous power is detected by detector and generates a current that is proportional to the instantaneous power. Each receiver can only sense the balance of the optical wave power without sense of the frequency of the phase related to it. Direct detection, where the

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output of a photo detector in response to an incoming optical field is a current proportional to the instantaneous optical power (i.e., proportional to the square of the electric field), is the most common and practical down-conversion technique.

The transmitted waveform *X (t)* is the instantaneous optical power of the light wave emitter. In general, the received waveform *Y (t)* is an instantaneous current in the photo detector at the receiving terminal, which is proportional to the integral of the surface over the total instantaneous optical power at all the spatial locations. The electric field incident typically has a space-varying magnitude and phase which would induce a multipath fading to a smaller than a wavelength sized detector [9]. Luckily typical detector regions are millions of square wavelengths so that a multipath fading is spatially un diversity. So, regardless of the distance that the detector is moved by the multipath, the distance optical wireless channels still suffer multipath distortion. The channel can be modeled as a baseband linear system, with instantaneous input power *X (t)*, output current *Y (t)*, and an impulse response *h (t)*, as shown in Fig.6

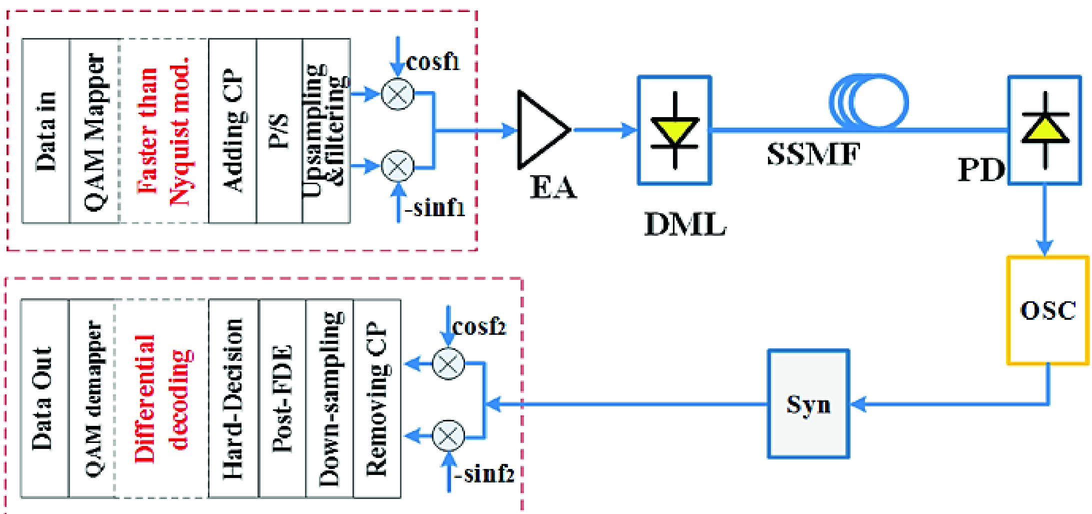

Figure (2): Intensity Modulation/ Direct Detection [4]

A large DC bias is usually added to OFDM signals requiring a high mean optical power [5][6][7] with a low modulation depth When the subcarriers of DC-biased O-OFDM (DCO-OFDM) [8][9] signals happened to be in phase, high peak-to-average power ratio (PAPR) [10][11] will bring serious signal distortion and performance deterioration, and result in non-linear distortion when the signals passing through the power amplifier or laser diode (LD). The transmitter of DCO-OFDM [12] [13] is depicted fig.1 the complex data signal $X = X_0, X_1, X_{2,\dots\dots,} X_{N-1}$ is input into the inverse fast Fourier transform (IFFT). X is constrained to have Hermitian symmetry [14], as defined below,

$$X_m = X^*_{N-m} \quad \text{for } 0 < m < \frac{N}{2}, \qquad (1)$$

and the two components X_0 and X_N are set to zero It should be noted that the output signal of the IFFT [15] , x, is real not complex. The researchers use upper case to represent a signal the corresponding lowercase

discrete time domain signal [16]. The k^{th} time domain sample of x, x_k, is represent as

$$x_k = \frac{1}{N}\sum_{m=0}^{N-1} X_m \exp\left(\frac{j2\pi km}{N}\right) \qquad (2)$$

Where N is the number of points on the IFFT and X_m is the m^{th} subcarrier of signal X. Due to the Hermitian symmetry X_0=X_N=0, the number of unique data carrying subcarriers present in DCO-OFDM is $N/2$-1. Signal x is then converted from parallel to serial(P\S) a cyclic prefix(CP) is appended, the resulting signal is digital to analog (D/A) converted [17] and low pass filtered resulting in $x(t)$ For large N values, the signal $x(t)$ can be modelled as a Gaussian random variable [18] with a zero mean and a variance of σ_D^2=$E[x_k^2]$. Next a suitable DC bias is added to $x(t)$ and any remaining negative peaks are clipped resulting in signal $X_{DCO}(t)$ Because OFDM signals have a very high peak-to-average power ratio, a very high bias is required to eliminate all negative peaks If a large DC bias is used [19], the optical energy-per-bit to single sided noise power spectral density $X_{b(opt)}/N_0$ [20], becomes very large, thereby making the scheme inefficient in terms of optical power [21]. The other negative peaks are clipped with the moderate bias normally used, which leads to the clipping noise [22]. Except for Type 3 DCO-OFDM systems, the clipping noise spreads across the entire bandwidth regardless of whether an odd or even subcarrier carries data symbols; i.e., both odd and even subcarriers are used to transmit data symbols [23]. The DC bias level is denoted by B_{DC}. B_{DC} is set relative to the standard deviation of $x(t)$.

$$B_{DC} = \mu\sqrt{E\{x(t)^2\}} \qquad (3)$$

where μ is a proportionality constant. B_{DC} is defined as a bias of $10\log_{10}(\mu^2 + 1)$ dB. Any resulting peak at which the is of B_{DC} is clipped at zero. Signal $X_{DCO}(t)$ is then input to an optical modulator. That the intensity of the output optical signal is directly proportional to the input electrical current. This generates a signal that is then sent through a flat channel. The shot noise is modelled as additive white Gaussian noise (AWGN) [24][25][26], $n(t)$ which is added in the electrical domain At the receiving end, the received signal is first converted (using a photodiode [27]) from optical to electrical. The processing after this point is the same as a conventional OFDM receiver. The PDF of $X_{DCO}(t)$ is a clipped Gaussian distribution given by:

$$f_{x_{DCO(t)}(v)} = \frac{1}{\sqrt{2\pi\sigma D}}\exp\left(\frac{-(v-B_{DC})^2}{2\sigma_D^2}\right)u(v) + Q\left(\frac{B_{DC}}{\sigma_D}\right)S(v) \qquad (4)$$

Where $u(v)$ is a unit step function and $S(v)$ is the Dirac delta function. The optical power of DCO-

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OFDM, $P_{opt,DCO}$, is given by,

$$P_{opt,DCO} = E\{x_{DCO}(t)\} = \int_0^\infty v\, f_{x_{DCO(t)}}(v)\,dv \tag{5}$$

$$= \frac{\sigma D}{2\pi}\exp\left(\frac{-B_{DC}^2}{2\sigma_D^2}\right) + B_{DC}\left(1 - Q\left(\frac{B_{DC}}{\sigma_D}\right)\right) \tag{6}$$

Where

$$Q(\zeta) = \frac{1}{\sqrt{2\pi}}\int_\zeta^\infty \exp\left(-\frac{u^2}{2}\right)du \tag{7}$$

The electrical power of DCO-OFDM, $P_{elec,DCO}$, is given by

$$P_{elec,DCO} = E\{x_{DCO}^2(t)\} = \int_0^\infty v^2\, f_{x_{DCO(t)}}(v)\,dv \tag{8}$$

$$= \left(\sigma_D^2 + B_{DC}^2\right)\left(1 - Q\left(\frac{B_{DC}}{\sigma_D}\right)\right) + \frac{\sigma_D B_{DC}}{\sqrt{2\pi}}\exp\left(-\frac{B_{DC}^2}{2\sigma_D^2}\right) \tag{9}$$

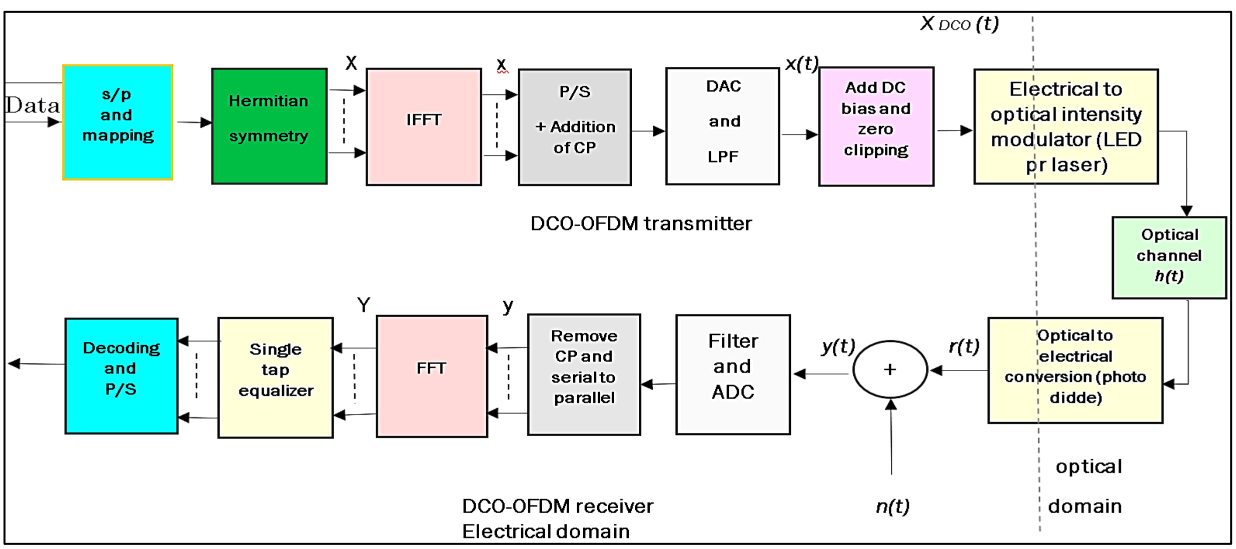

Figure (3): DCO-OFDM system [28]

Table (1): Direct Clip Optical-OFDM (DCO-OFDM)

Reference	Method	Brief description	advantages	Weakness
[12]	The subcarrier spaced spatial grouping (SSG) based DCO-OFDM.	The OFDM signals can be separated into multiple low-PAPR narrowband independent signals simultaneously. ZF is used at the RX side while signal is transmitted.	proposed approach achieves lower PAPR	The spectral efficiency cost is a small degradation compared to the counterpart
[29]	SCR and Tone reservation scheme based LSAusing DCO-OFDM	The transmitter of the DCO-OFDM Then, it puts the indoor VLC in such a way that, the PAPR reduced signal at the cost of multiplying the transmission bandwidth	The PAPR is effectively reduced	This is the behaviour of BER with distance for the communication system.
[30]	Auto-encoder network with (ESLM-AE) based on DCO-OFDM	with (ESLM-AE) based on DCO-OFDM an ESLM-AE, for the reduction of the PAPR	The PAPR is remarkably reduced	On the other hand, it degrades the BER of the system as well as it has a high computational complexity
[31]	TR based TKM for DCO-OFDM	For constructing the PSO based on TKM-TR schemes have been proposed for the System Applying Modified Phase Rotation Matched Filtering in a DCO-OFDM To Mitigate The PAPR	The PAPR has been mitigated	PSO iteration takes a long time, i.e., high execution process time. Moreover, system BER was degraded
[32]	M-OSLM And FBMC for DCO-OFDM	the M-OSLM suppression algorithm to mitigate the high value of PAPR uses offset (OFDM/OQAM) of (FBMC), which is based on TFL filter- to overcome ISI and ICI	The PAPR restrain and use of ISI is but natural.	SLM is inherently complex
[33]	BBM-based TI in VLC DC-OFDM	Proposed TI method based on BBM to mitigate the PAPR	The PAPR significantly reduced	This led to an increase in its BER Performance when compared to some other system.
[34]	OEOSC for SLM based DCO-OFDM VLC system	not offer further side information other than that linear combination in time domain Cyclic shift and Phase rotation of Even and Odd Sequences	Got lower complexity	The PAPR and BER are not improved The improvement of PAPR Results After high-order ultra-microwave is normal.
[35]	E-DCO-OFDM for VLC	imaginary value only, which are real-valued signals multiplied by a scaling factor, are modulated onto an ellipse.	Significantly reduce the PAPR	Half of subcarriers not used
[36]	TSDA based DCO-OFDM for VLC	PAPR reduction technique based on Detection and appending of Top sampling (TSDA	achieve less complex and lower PAPR	Hence, complexity and deteriorating BER are the problems that still exist with the system considered above

To solve the concern of the high PAPR together with the low linearity for LED, the authors in [12] propose an SSG solution. The high-PAPR wideband OFDM signals is divided into several low-PAPR narrowband independent signals that are simultaneously sent from different LED light sources. Zero-forcing (ZF) employed at the receiver for compensating the channel transform can then be followed to that end by the DCO-OFDM system that offers substantial gains in PAPR and BER performance at the cost of spectral efficiency. A combined SCR → LSA SCR procedure is proposed in [29] for PAPR reduction scheme. The two TR methods are jointly used to enhance the PAPR reduction performance efficiently, but it does not overlap twice the area bandwidth, whereas the BER is calculated depending on the communication distance of DCO-OFDM-VLC system.

Then, ESLM-AE is a deep neural network (DNN) that is trained to solve the problem of high PAPR of DCO-OFDM signals [30]. The AE structure in the AE structure is used to denote constellation mapping and de-mapping of the transmitted symbols [33]. In this work, we propose a PSO based tone reservation (TKM-TR) leveraging the TKM to reduce the PAPR, and the PSO is employed to search a better CR to reduce the PAPR. Also, an enhanced TKM-TR scheme is illustrated for the peak regrowth mitigation. Also, since the CR value is closely associated with the performance of PAPR decrease, it can also be seen as this method gets better PAPR minimize compared to conventional method while desired small deterioration in BER [30]. The authors of [31] presented a prototype for a new waveform which used time frequency localization (TFL) to produce filter bank multicarrier technology (FBMC) OFDM/OQAM to minimize ISI and ICI. In this paper, we propose the M-OSLM suppression algorithm to constrain the peak to average power ratio (PAPR); the simulation results reveal that the DC-biased optical OFDM/OQAM (DCO-OFDM/OQAM) possesses the stronger anti-inter-symbol interference (ISI) capability than its counterparts.

Furthermore, M-OSLM algorithm has significantly enhanced the PAPR reduction performance, but SLM complexity is inescapable. A bandwidth-efficient BBM-based (tone injection) (TI) PAPR-reduction methods for VLC DCO-OFDM system [32]. Problem of reducing PAPR is mathematically described as a non-trivial integer combinatorial optimization problem. We propose a branch-and-bound method (BBM) to tackle this issue and realize an impressive PAPR reduction above 10 dB all the while preserving y the BER performance w respect to TI scheme only. An optimized even and odd sequence combination (OEOSC) technique for the DCO-OFDM VLC systems was proposed by the authors so as to alleviate the SI transmission and a large computational complexity (CC) [37] through linear combinations of the time-domain even-odd decompositions with respective cyclic delay and phase shift [38]. This method has high CC which reduces PAPR and BER but low CC is also achieved by this low CC approach with high CC because of IFFT taking on even and odd entries of the Hermitian symmetry coded signal [39], [33]. In comparison to DCO-OFDM, the proposed method achieves the optimal major and minor axis ratio of ellipse by mapping the real-valued signal onto an ellipse, and only transmits the relevant imaginary valued point on the ellipse [40]; this ellipse-DCO-ODFM method achieves better performance in terms of PAPR and BER at the cost of using half of subcarrier.

In [34], the authors provided a new PAPR reduction without the help of side information, called top samples detection and appending (TSDA). The PAPR reduction method firstly identifies the best samples and then uses it to minimize the PAPR [41]. Therefore, the number of candidate signals times system of DCO-OFDM scale down the computational complexity by not using them in the proposed technique. The simulation result has low complexity with respect to ordinary PTS [41] and SLM [42]. In addition, PAPR is less compared to previous case, but high complexity is present in the system and BER gained is 0.

Table (2): shows the application and the benefit of the approach

Application	Primary Benefit of DirectClip	Target Outcome
6G Fronthaul	Cost-effective IM/DD at Tbps speeds	99.9999% Reliability
Data Centers	Low-power signal processing	Reduced Thermal Footprint
Li-Fi	LED Non-linearity Mitigation	High-speed Indoor Wireless
Automotive	Low-complexity DSP for POF	EMI-Immune Sensor Links

3. Applications in Next-Generation Connectivity

1. **5G/6G Optical Front Haul Networks:**

   In the transition to 6G, the "front haul" (the link between the Central Unit and the Radio Units at the tower) must handle data rates approaching 1 Tbps. However, the large scale Densification of 6G means that the small cells need ultra-dense deployment. It is not possible, of course, to deploy high-end coherent optical transceivers at every cell. Furthermore,, Link able to utilize Intensity-Modulation Direct-Detection (IM/DD) [43] a fraction of the cost solution compared to coherent detection while sustaining the high performance necessary to achieve the extremely low latency (<100 μs) and ultra-high reliability supported by the 6G.

2. **Hyperscale Data Centre Interconnects (DCI):**

   A key challenge in modern AI-driven data centres is a "thermal wall." Each watt utilized in signal processing is simply a watt that should have gone to a GPU. Direct Clip lowers PAPR reduction computational requirements compared to more complex iterative algorithms while still being considered simplified DSP. In addition, it allows lower-resolution Digital-to-Analog Converters (DACs), nonlinear uncooled lasers, and Agnostic in hardware. This lowers the CapEx (upfront cost) and OpEx (electricity and cooling) for the optical fabric of the data center.

3. **Optical Wireless Communication (Li-Fi):**

   Li-Fi technology uses LEDs or Infrared Laser Diodes to transmit data with light. Nonetheless, LEDs are very non-linear devices, and this leaves a small dynamic range. Flicker-Free Transmission: High-amplitude peaks across the OFDM signal may cause the LED to operate out of its standard operating window and induce flicker; by "clipping" the OFDM signal in a controlled manner, the Direct Clip method ensures that the LED remains in its optimal operating window. Additionally, for FSO (Free-Space Optics) outdoor, the signal is faded due to atmospheric turbulence. The DirectClip can extract absolute maximum signal power from very tight limits, allowing DirectClip to remain much less affected by the shining air, or "shimmering" effect.

4. **Autonomous Vehicles & Software-Defined Vehicles (SDV):**

   Automotive Optical Ethernet replaces internal copper wiring as Cars become data centers on wheels. Optical Fiber being non-metal and plastic in nature, doesn't get affected by the EMI (Electromagnetic Interference (EMI) found in any electric vehicle engines are stopped due to EMI Immunity. Direct Clip Integration enables magnetorestrictive 4K cameras and LiDAR to operate in multi-gigabit (e.g. the 10GBASE-AU standard) Data streams across POF (Plastic Optical Fiber) at high-speeds (with fluctuations) on automotive-grade LED with a low-complexity interface.

5. **Industrial IoT & Smart Manufacturing:**

   When it comes to "Industry 4.0" settings, heavy machinery still cause most Wi-Fi or 5G signals to be broken by radio interference. Direct Clip Optical-OFDM enables high-speed communication through existing lighting infrastructure (VLC) 45 that does not suffer from interference when using reliable Light-Pipes [44]. It enable cost effective high-density Machine-Type Communication (mMTC) and eliminates the possibility of RF congestion. The Performance Comparison section provides a more granular view into the exact metrics that explain the broader media interest in why DirectClip Optical-OFDM looks to be winning out here, as well as what other key metrics make this seem like a winning approach compared to DCO-OFDM.

4. The primary Trade-off in these Systems is between Hardware Complexity and Error Performance

1. **Peak-to-Average Power Ratio (PAPR) Reduction:**

   Without inserting any peak power control, in common DCO-OFDM, the PAPR is more than 10–13 dB, which is beyond the linear range of most economical LEDs or Laser Diodes [47]. DCO-OFDM: Requires high DC biasing which moves the whole signal to the positive region. This brute force approach uses a lot of power and still has high peak clipping risk. Through deliberate digital clipping, the PAPR can be constrained to a constant 3–5 dB This is known as the Direct Clip technique. This stops the signal from reaching the optical emitter "saturation ceiling", thereby cleaning up the signal before it is even converted to light.

2. **Optical and Electrical Power Efficiency:**

   This is only useful in so far as working out the efficiency: how much data-carrying light comes out, and how much is wasted as DC heat. DC Bias Savings: The conventional DCO-OFDM needs a large DC offset (7 dB or even larger in many cases [3]) to prevent negative peak from clipping. Because it bypasses any negative excursions mathematically, Direct Clip enables the system to

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run at a significantly reduced DC bias. Energy per Bit: For Direct Clip, it can boost the energy efficiency for high-order modulations (such as 1024-QAM leveraged in 5G) about 15–20% compared with un optimized systems since in un optimized systems, the "dead power" stored in the DC bias is still held [32]..

3. **Bit Error Rate (BER) vs. SNR Trade-off:**

The key measure for any researcher is the Signal-to-Noise Ratio (SNR) [48] necessary to achieve some target BER (usually 10−3 for Forward Error Correction). Clipping Penalty: Clipping -- this creates noise Direct Clip, however, uses Iterative Clipping and Filtering (ICF) [49] or Noise Shaping [50] to shift that noise to the unused subcarriers.

Direct Clip systems generally provide 2–3 dB SNR advantage over DCOOFDM at high SNR. This is to say that with a weaker signal or a longer distance, you can still accomplish the same quality in data.

4. **Hardware & Computational Complexity:**

And this is where Direct in Direct Clip shines. Standard DCO-OFDM typically requires 8–10 bit DACs to accommodate high-amplitude peaks. Direct Clip can support as low as 4–6 bit DACs that are more low-cost, smaller, and lower power. In terms of DSP Overhead, While Direct Clip is somewhat more taxing (clipping and filtering steps) on the digital side, this is a one-time computational overhead within the transmitter that arewell within the capabilities of modern FPGAs [51] or ASICs rather than the continuous power load of a high-bias laser.

Table (3): Shows the enhancement of DCO- improvements

Performance Metric	Traditional DCO-OFDM	Direct Clip Optical-OFDM	Impact on Next-Gen Networks
Typical PAPR	10–13 dB	3–5 dB	Enables use of low-cost LEDs
DC Bias Requirement	High (Significant)	Low (Minimized)	Reduces thermal/heat issues
Spectral Efficiency	High	High (Maintained)	Maximize bits per Hertz
DAC Resolution	High (8-10 bits)	Low (4-6 bits)	Lowers CapEx for hardware
BER at High SNR	Limited by Saturation	Improved (Clean peaks)	Increases link reliability
Non-linear Resilience	Poor	Excellent	Perfect for VLC and Li

5. Conclusion

This review shows that while DCO-OFDM has been the foundation of most high-speed IM/DD systems, its practical performance is inherently restricted by high PAPR and subsequent nonlinearity of optical sources. This shift towards Direct-Clip structures is a seminal development in DSP, providing a sophisticated framework to address, via clipping and noise shaping, the aforementioned limitations. Direct-Clip achieves this by reducing the dependence on high DC bias, which contributes to ameliorate electrical power efficiency (estimated cost-benefit 15–20% in average) and permits the adoption of low-cost and low-resolution hardware without altering the Bit Error Rate (BER). With 6G front-haul and widespread Li-Fi soon on the horizon, Direct-Clip integration will help bridge the gap between the harsh demands of ultra-high throughput and the limits of non-linear optical components.

6. Recommendations

According to the trajectory of optical wireless research, it is proposed that a future study could emphasize the integration of lightweight machine learning models tasked with adaptively optimizing the clipping ratio in real-time for dynamic 6G environments. It becomes essential to develop a standard benchmarking solution that extends beyond simple BER analysis to include "green" metrics, such as power-added efficiency, and engage with the thermal challenges that modern data centers face. Furthermore, The experts should explore Hardware-in-the-Loop (HiL) validation to characterize signal integrity using cheaper automotive grade LEDs and uncooled lasers. Lastly, the interaction between the Direct-Clip technique and other waveforms like FBMC may lead to substantial gains in spectral leakage and ISI mitigation suitable to the next generation of software-defined optical networks.

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