

Proceeding Paper

Performance Analysis of DCO-OFDM in IEEE 802.11bb VLC PHY Modes: Impact of Biasing Techniques and Optical Channel Dispersion [†]

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Abstract

This paper presents a performance analysis of Direct Current-biased Optical OFDM (DCO-OFDM) under the IEEE 802.11bb standard for Visible Light Communication (VLC). The study covers all physical layer (PHY) modes (HT, VHT, and HE) through a complete simulation of the PHY processing chain, including scrambling, convolutional encoding, interleaving, and modulation. These results provide a standard-driven recipe to tune VLC transmitters while preserving IEEE 802.11bb interoperability. To the best of current knowledge, this is among the first IEEE 802.11bb-compliant evaluations of DCO-OFDM for VLC that jointly examine DC-biasing strategies and optical channel dispersion across HT/VHT/HE modes. The novelty lies in the presentation of practical and standard-oriented standard-based design guidelines for transmitter optimization under IEEE 802.11bb, rather than a new analytical model. This work provides one of the first IEEE 802.11bb-compliant evaluations of DCO-OFDM in VLC that jointly studies DC-biasing (static/dynamic/clipping) and optical dispersion ($L = 1/3/5$) across HT/VHT/HE, reporting SNR@BER = 10^{-3} baselines, a mean B_{CD} power proxy, and actionable bias-channel-mode design guidelines.

Keywords: Visible Light Communication (VLC); IEEE 802.11bb; DCO-OFDM; DC biasing; PHY layer; BER; OFDM; Modulation/Direct Detection (IM/DD); MATLAB simulation



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1. Introduction

Visible Light Communication (VLC) uses the visible spectrum (380–780 nm) through LED infrastructure to deliver high-speed wireless links [1]. VLC offers unlicensed spectrum, natural 38 spatial confinement, and immunity to RF interference, which makes it suitable for short-range indoor environments where traditional RF may face regulatory or performance constraints.

The IEEE 802.11bb amendment integrates VLC into WLANs by standardizing both PHY and MAC for optical wireless communication [2]. The PHY defines three operation modes—High Throughput (HT), Very High Throughput (VHT), and High Efficiency (HE)—all based on OFDM to provide robustness against multipath and high spectral efficiency [2,3]. Each mode targets distinct performance requirements and channel conditions within a unified Wi-Fi framework.

OFDM generates bipolar waveforms that violate the non-negativity constraint of Intensity Modulation/Direct Detection (IM/DD) used in VLC [4]. Direct Current-biased Optical OFDM (DCO-OFDM) addresses this by adding a DC component that shifts the waveform above zero, preserving compatibility with optical frontends [4].

Prior DCO-OFDM studies often rely on generic or ad hoc configurations. Several works analyze biasing techniques, modulation formats, and optical dispersion to explain BER trends and power efficiency [5,6], while others explore adaptive scaling or clipping to reduce distortion and save power in IM/DD links [7,8]. These contributions are valuable but are not directly comparable to standard-based deployments due to custom assumptions.

This study provides one of the first IEEE 802.11bb-compliant end-to-end evaluations of DCO-OFDM for VLC, using the official PHY modes (HT/VHT/HE), standard pilot structure, coding, and cyclic prefix. The analysis centers on how DC-biasing strategies interact with optical channel dispersion to shape BER performance within a standardized Wi-Fi-VLC framework.

The main contributions are as follows: (i) a fully IEEE 802.11bb-compliant PHY implementation for VLC—covering OFDM, standard pilots, cyclic prefix, convolutional coding, interleaving, and scrambling; (ii) a joint bias-channel analysis that quantifies static, dynamic, and no-DCO (clipping) strategies across flat ($L = 1$), moderately dispersive ($L = 3$), and highly dispersive ($L = 5$) optical channels with BER-SNR curves; (iii) standard-based design guidelines that map channel condition and SNR regime to the recommended PHY mode and bias strategy, clarifying robustness-throughput-power trade-offs across HT/VHT/HE; and (iv) brief complexity/power notes contrasting per-packet (static) versus per-symbol (dynamic) overhead and discussing implications of the mean DC level.

2. Literature Review

Beyond optical-OFDM baselines and bias-selection for IM/DD links [6,8], post-802.11bb work has focused on reference indoor channel models [9], LiFi channel flatness and CP adequacy under 802.11bb assumptions [10], and tutorials situating 802.11bb within the Wi-Fi family and deployment challenges [11]. However, these studies either lack BER-vs-SNR under a fully standard-compliant PHY or omit a joint comparison of static vs. dynamic DC-biasing across flat/moderately/highly dispersive channels and all three PHY modes. This work closes that gap by keeping full 802.11bb compliance (HT/VHT/HE; pilots/CP/coding/rates) and quantifying bias-channel-mode trade-offs via BER-SNR and $\text{SNR@BER} = 10^{-3}$ to derive practical transmitter design guidelines. A comparative summary of prior work and our study is provided in Table 1

Table 1. Comparative summary of related works and the present study: standards/scenarios, biasing strategies, channel models, metrics, and uncovered aspects.

Reference	Standard/Scenario	Biasing Channel Model	Metrics	Not Covered in That Work
[9] IEEE 802.11bb Reference Channel Models (Tech Report)	Reference indoor dispersion models for 802.11bb	—	Channel modeling guidance	No BER/SNR evaluation; no static vs. dynamic bias; no cross-mode (HT/VHT/HE).
[10] WCNC'20: LiFi Channel Flatness for 802.11bb	Flatness vs. CP adequacy (indoor)	—	Flatness/CP criteria	No BER@SNR; no bias strategy comparison; typically, single-PHY focus.

Table 1. Cont.

Reference	Standard/Scenario	Biasing Channel Model	Metrics	Not Covered in That Work
[11] IEEE Communications Standards Magazine: 802.11bb Status/Challenges	Standard overview	—	—	No empirical BER/SNR; no bias analysis; no multi-mode results.
[8] OFDM for Optical Communications (Tutorial)	DCO-OFDM baseline	Typical indoor	BER/PAPR (review)	Not 802.11bb-compliant; no joint bias-channel-mode analysis.
[6] Adaptive Scaling & Biasing for VLC (Opt. Express 2014)	Adaptive DC-bias	AWGN/flat (typ.)	BER vs. SNR	Not 802.11bb; limited dispersion; no cross-mode.
This work	IEEE 802.11bb HT/VHT/HE (standard-compliant)	DCO-Static, DCO-Dynamic, No-DCO (clipping) L = 1 (flat), L = 3 (moderate), L = 5 (dispersive)	BER vs. SNR; SNR@BER = 10 ⁻³ ; mean-BCD power proxy; complexity note	Systematic joint analysis of bias + channel + modes under 802.11bb.

3. DCO-OFDM Principles and IEEE 802.11bb PHY Layer

Optical Wireless Communication (OWC) transmits data using light in the visible, infrared, or ultraviolet bands [4]. Within OWC, VLC operates in the 380–780 nm range using LED emitters whose low-frequency modulation is imperceptible to humans yet detectable by photodiodes, enabling high-speed indoor links [1,2]. IM/DD dominates VLC for its simplicity and low cost but requires real, non-negative time-domain signals [12]. Consequently, conventional RF OFDM—complex-valued and bipolar—cannot be applied directly, motivating adaptations such as Direct-Current-biased Optical OFDM (DCO-OFDM) [5–7,12]. Under IM/DD, the VLC channel is treated as an LTI system; see Equation (1).

$$y(t) = R * x(t) \otimes h(t) + n(t), \quad (1)$$

Variables: $y(t)$: received current; R : photodetector responsivity (A/W); $x(t)$: transmitted optical intensity; $h(t)$: optical channel impulse response; $n(t)$: AWGN; $\otimes$: time-domain convolution [5].

3.1. Modulation DCO-OFDM in VLC Systems

DCO-OFDM is a waveform adaptation technique specifically designed to make OFDM compatible with the requirements of VLC that rely on IM/DD [5].

In conventional OFDM, the transmitted signal is generated by modulating information onto multiple orthogonal subcarriers, typically using schemes such as Quadrature Phase Shift Keying (QPSK) or higher-order QAM [3,4]. The modulated frequency-domain symbols are then converted into a composite time-domain signal via the Inverse Fast Fourier Transform (IFFT), producing a complex-valued and bipolar waveform [5,6]. The time-domain OFDM signal $x(m)$ is computed as the inverse transform of the complex symbols X_k , and is mathematically expressed in Equation (2) as [5,13]:

$$x(m) = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j \frac{2\pi k m}{N}} \quad 0 \leq m \leq N-1 \quad (2)$$

Variables: $x(m)$: time-domain OFDM sample at index m ; X_k : complex data/pilot on subcarrier k ; N : IFFT size (number of subcarriers); $0 \leq m \leq N-1$; $j = \sqrt{-1}$.

VLC systems do not support bipolar or complex signals; therefore, the transmitter applies Hermitian symmetry at the input of the IFFT [6]. This operation ensures that the IFFT output remains purely real, which guarantees compatibility with the requirements of Intensity Modulation and Direct Detection (IM/DD) systems. The frequency-domain vector is presented in Equation (3), which is constructed as [5,6]:

$$X_H = [0, X_1, X_2, X_3, \dots, X_{\frac{N}{2}-1}, 0, X_{\frac{N}{2}-1}^*, \dots, X_3^*, X_2^*, X_1^*] \quad (3)$$

Variables: X_H : Hermitian-symmetric frequency vector; entries $X_1, \dots, X_{N/2-1}$ carry data; the DC bin ($k=0$) and the Nyquist bin ($k=N/2$) are set to zero to enable a strictly real time signal; $(\cdot)^*$: complex conjugate.

The first zero corresponds to the DC component, while the second zero corresponds to midpoint of the spectrum, that is, the first Nyquist frequency. This redundancy ensures that the IFFT output satisfies the conjugate symmetry condition, like in Equation (4):

$$X_k = X_{N-k}^* \quad 1 \leq k \leq \frac{N}{2} - 1 \quad (4)$$

As a result, the IFFT produces a real-valued signal $x(m)$, defined in Equation (5).

$$x(m) = \frac{1}{N} \sum_{h=0}^{N-1} X_H(h) e^{j \frac{2\pi k m}{N}} \quad m = 0, \dots, N-1 \quad (5)$$

Variables: $x(n)$: real time-domain OFDM symbol obtained from the IFFT of X_H ; IFFT size; n : time index; k : subcarrier index used in the exponential sum. (This construction guarantees a real-valued waveform for IM/DD.)

This transformation ensures that all imaginary components in the time domain cancel out, leaving a purely real waveform. However, since the signal may still contain negative values, an additional step—adding a positive DC bias—is required to ensure that the final signal used for optical modulation is non-negative across all time samples [5].

3.2. Biasing Techniques for Optical OFDM Transmission

The transmitter adds a direct current (DC) bias to the signal produced by IFFT. The system calculates the bias level using the following expression. The biased signal is defined in Equation (6) [5]:

$$x'(m) = \alpha * x(m) + B_{CD} \quad (6)$$

Variables: $x'(m)$: bias-added (non-negative) waveform for IM/DD; $x(m)$: real IFFT output (can be negative); $\alpha > 0$: scaling/safety factor; $B_{CD} \geq 0$: added DC-bias level.

A DC bias is added to the signal obtained at the output of the IFFT, which is calculated as Equation (7) [5]:

$$B_{CD} = \alpha * \sigma_X \quad (7)$$

Variables: σ_X : the standard deviation of $x(m)$; α : safety factor (2 or 3) that controls the signal amplitude (compensating energy and controlling clipping probability) and ensures the signal is strictly positive; B_{CD} : DC-bias ensuring non-negativity of $x'(m)$.

Three biasing strategies can be considered:

- **Static biasing** applies a constant DC value to every OFDM symbol. This straightforward technique ensures compatibility with IM/DD, although it may result in increased power consumption [2].

- **Dynamic biasing** adjusts the DC level for each symbol individually. This method improves energy efficiency but introduces additional computational complexity [6].
- **Zero biasing**, which clips negative signal values, reduces power usage but causes distortion. Moreover, it does not meet the compliance requirements of the IEEE 802.11bb standard [5,6].

3.3. PHY in IEEE 802.11bb

The IEEE 802.11bb standard [2] is an amendment to the IEEE 802.11 family to support OWC using visible light. It defines PHY and MAC layers, required to enable high-speed indoor communication using LED-based infrastructure and photodetectors. Unlike earlier approaches to VLC that relied on proprietary designs or lacked interoperability, IEEE 802.11bb ensures seamless integration with existing Wi-Fi infrastructure by preserving compatibility with the broader IEEE 802.11 MAC architecture [2].

In the case of IEEE 802.11bb, it defines three PHY operation modes: HT, VHT, and HE, each designed for specific performance goals and application environments. The parameters of each mode are presented in Table 2. These modes are built upon Orthogonal Frequency Division Multiplexing (OFDM) [2].

Table 2. PHY HT, VHT and HE parameters of 802.11bb parameters [2].

Parameter	HT PHY	VHT PHY	HE PHY
Bit Rate (Mbps)	6 to 54	6 to 54	6 to 54
Modulation Modes	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM	BPSK, QPSK, 16-QAM, 64-QAM
Code Rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	1/2, 2/3, 3/4
Number of Subcarriers (Nfft)	64	128	64
Cyclic Prefix Length	1/4 (16 samples)	1/8 (16 samples)	1/8 (8 samples)
Symbol Duration	8 μ s	8 μ s	8 μ s
Guard Interval	2 μ s	1.6 μ s	1 μ s
FFT Period	6.4 μ s	6.4 μ s	7 μ s
Pilot Positions	[13, 26, 40, 54]	[11, 25, 39, 53]	[8, 22, 44, 58]
Biasing Type	Static DC Bias	Static DC Bias	Static DC Bias

Figure 1 illustrates a generic block diagram of the IEEE 802.11bb PHY transmitter. The processing chain begins with a Forward Error Correction (FEC) encoder. Then, it undergoes interleaving, which disperses burst errors across multiple symbols, followed by constellation mapping (e.g., BPSK, QPSK, 16-QAM) to generate complex modulation symbols [2]. These symbols are transformed into the time domain using an IFFT, which produces a bipolar signal across multiple subcarriers [2]. To ensure real-valued output is suitable for intensity modulation, Hermitian symmetry is applied prior to the IFFT (not explicitly shown in the diagram but implied in the mapping stage) [2]. The resulting OFDM symbols are then processed with the insertion of a cyclic prefix—and optionally a windowing function to suppress spectral leakage and mitigate inter-symbol interference (ISI) due to multipath effects [2]. Next, a DC bias is added to the real-valued signal, shifting the waveform into the non-negative domain required by IM/DD systems [2]. Finally, the signal is sent to the optical front-end, where it directly modulates the intensity of a light-emitting diode (LED) or is processed by an optical front-end (OFE) driver for physical transmission over the VLC channel [2].



Figure 1. Transmitter block diagram for DCO-OFDM in IEEE 802.11bb VLC PHY [2].

4. Implementation of DCO-OFDM in IEEE 802.11bb PHY Modes Using MATLAB

The MATLAB (R2024b, Version 24.2; The MathWorks, Inc., Natick, MA, USA) framework models the IEEE 802.11bb PHY end-to-end—transmission, reception, and channel—and adheres to the block architecture of the standard. The three PHY modes (HT, VHT, HE) serve as a compliance envelope, while the analysis centers on the IM/DD constraints of VLC, namely the need for real-valued, non-negative waveforms.

The system generates random bits, applies scrambling, and performs convolutional coding with puncturing to reach the target rate. Next, interleaving mitigates burst errors and QAM maps the coded bits to complex symbols. The symbols are placed on data subcarriers with pilot insertion as mandated by each PHY. Hermitian symmetry enforces a real time-domain OFDM signal. An IFFT produces the time sequence, and a cyclic prefix (CP) protects against ISI. Figure 2 indicates the dataflow jump between rows (from QAM to subcarrier assignment).

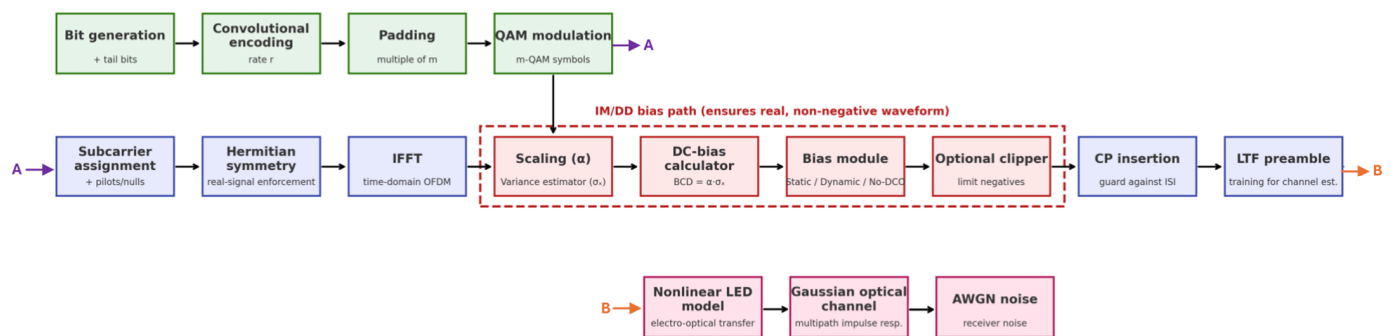


Figure 2. IEEE 802.11bb DCO-OFDM transmitter for VLC: green = source/coding; indigo = OFDM baseband; red (dashed) = IM/DD bias path; orange = optical front-end and channel. A/B markers denote row-to-row data jumps; the vertical QAM→Scaling arrow sets α from modulation/power normalization; the IFFT→Scaling arrow feeds σ_x for $B_{DC} = \alpha\sigma_x$ [1,2].

IM/DD bias path (red dashed box) enforces a non-negative electrical waveform for intensity modulation. A per-symbol variance estimator computes the time-domain standard deviation σ_x and a target bias ratio α is selected, linked to the desired clipping ratio and EVM objective. The DC offset is then computed as $B_{DC} = \alpha\sigma_x$ and added to the waveform by the bias module. Three operating modes are implemented: **Static** (fixed α throughout), **Dynamic** (updates B_{DC} every OFDM symbol using the measured σ_x ; α may also adapt per symbol), and **No-DCO** ($\alpha = 0$) as a baseline. An optional clipper removes any residual negative samples and constrains PAPR to preserve LED linearity.

The vertical arrow from QAM to Scaling represents control information, not a sample stream: the modulation order and power normalization selected at QAM inform the choice of α so that the clipping probability/EVM target remains consistent across PHY modes and constellation sizes. The horizontal arrow from IFFT to Scaling conveys the time-domain statistics used to estimate σ_x . The nonlinear LED model applies the electro-optical transfer of the emitter; the Gaussian optical channel uses a multipath FIR with L taps (here, “channel length” equals number of taps and determines dispersion); AWGN noise models receiver noise. The B markers connect the PHY preamble (LTF preamble) with the optical path, emphasizing its role in channel training before detection.

4.1. Optical Channel Conditions

The characteristics of the optical wireless channel significantly affect the performance of VLC systems. Depending on the propagation environment, the channel impulse response $h(t)$ can range from highly concentrated (flat) to heavily dispersed, leading to varying degrees of inter-symbol interference (ISI). In this study, we consider three representative channel conditions [12].

- **Flat (Line-of-Sight, LOS):** Under ideal conditions where a direct LOS path dominates, the impulse response closely resembles a delta function (Equation (8)).

$$h(t) \approx h_0 \delta(t) \quad (8)$$

This implies negligible delay spread $\tau_{rms} \approx 0$. Thus, ISI is practically nonexistent, and the system behaves as a memoryless channel.

- **Moderately Dispersive Channel:** This case includes a dominant LOS path with additional weak multipath reflections. The impulse response can be modeled like Equation (9):

$$h(t) = h_0 \delta(t) + \sum h_i \delta(t - \tau_i), \text{ where } |h_i| \ll |h_0| \quad (9)$$

The RMS delay spread is moderate as $0 < \tau_{rms} < T_{CP}$. Some ISI occurs but can be mitigated with proper OFDM design.

- **Highly Dispersive Channel:** When reflections have similar amplitude to the LOS path, the channel becomes severely dispersive (Equation (10)):

$$h(t) = \sum h_i \delta(t - \tau_i), \text{ where } |h_i| \approx |h_0| \quad (10)$$

Variables for Equations (8)–(10): $h(t)$: Channel impulse response (CIR) in the time domain; h_0 : Complex (or real, for IM/DD baseband) gain of the dominant LOS path (units: dimensionless gain); h_i : Complex/real gain of the i – th multipath component (units: dimensionless gain); $\delta(t)$: Dirac delta function; $\delta(t - \tau_i)$: Impulse located at delay τ_i for the i – th path; τ_i : Propagation delay of the i – th path (units: s); L = Number of resolvable channel taps/paths; τ_{rms} : Root-mean-square (RMS) delay spread of the channel (units: s).

Table 3 summarizes the three channel cases and the DC-biasing modes used in our simulations and lists the specific channel dispersion (L) and biasing configurations adopted in the experiments.

Table 3. Optical channel dispersion (L taps) and DC-biasing configurations for standardized (IEEE 802.11bb) DCO-OFDM simulations [2,6,12].

Parameter	Category	Parameter	Value
Flat LOS	Channel	Number of taps L (dispersion)	1
Moderate Multipath	Channel	Number of taps L (dispersion)	3
Highly Dispersive	Channel	Number of taps L (dispersion)	5
DCO-Static	Biasing Strategy	DC bias (B_{CD})	Fixed per packet: $B_{CD_{STATIC}} = \alpha \cdot \sigma_x^{pkt}$
DCO-Dynamic	Biasing Strategy	DC bias (B_{CD})	Updated per symbol: $B_{CD_{dym}} = \alpha \cdot \sigma_x^m$
No-DCO (clipping)	Biasing Strategy	Output constraint	Negative samples clipped to 0 (non-compliant; stress case)

Note: σ_x^{pkt} = per-packet standard deviation; σ_x^m = per-symbol standard deviation (symbol m).

4.2. Power-Efficiency Metric

We report a simple, implementation-oriented power metric based on the average optical output required by IM/DD biasing. Let $x(n)$ be the real IFFT output and $x'(n) = \alpha \cdot x(n) + B_{CD}$ the biased waveform. Since $\mathbb{E}[x(n)] = 0$ after the IFFT, the average optical power is proportional to the meaning of the biased signal, where

$$\overline{P_{opt}} \propto \mathbb{E}[x'(n)] = \alpha \mathbb{E}[x(n)] + B_{CD} = B_{CD} \quad (11)$$

Thus, the DC-bias value directly reflects power usage. We compare strategies through a relative indicator.

$$\eta_{DC} = 100 * \left(1 - \frac{\overline{B_{CDdynamic}}}{B_{CDdynamic}} \right) [\%] \quad (12)$$

Here is the fixed per-packet bias; the per-symbol bias averaged over the frame. Interpretation: **Static** bias is robust but tends to $\overline{P_{opt}}$ (larger B_{CD}). **Dynamic** bias adapts per symbol, potentially lowering “idle” DC and improving η_{DC} (power saving) in flat channels. There is no report η_{DC} qualitatively (low/medium/high) when numerical logging of B_{DC} is not enabled, and quantitatively (as %) when available.

4.3. Computational Complexity of Biasing

The overhead contrast is introduced by DC-biasing with the dominant PHY blocks (IFFT and FEC). Let N be the IFFT size. IFFT baseline (per symbol): $C_{IFFT} \approx \mathcal{O}(N \log_2 N)$. Besides, in DCO-Static $C_{\sigma}^{static} = \mathcal{O}(N_{pkt})$ with one σ_x per packet $C_{BCD}^{static} = \mathcal{O}(1)$ per packet and $C_{add}^{static} = N$ adds per symbol ($\mathcal{O}(N)$). In other case, the DCO-Dyn has $C_{\sigma}^{static} = \mathcal{O}(N_{pkt})$ with variance per symbol; $C_{BCD}^{dyn} = \mathcal{O}(1)$ with update per symbol and $C_{add}^{dyn} = N$ adds per symbol ($\mathcal{O}(N)$). Finally, Relative to the IFFT ($\approx \mathcal{O}(N \log_2 N)$) and the channel coding/decoding costs, the extra operations required by biasing—particularly in the dynamic case—remain **moderate**. In practice, **dynamic** bias trades a small computational overhead for potential power savings (lower mean B_{DC}) in flat channels, whereas **static** bias favors robustness in dispersive channels.

5. Simulation Results

We include all IEEE 802.11bb PHY modes (HT/VHT/HE) for strict compliance, but the analysis centers on how DC biasing and optical-channel dispersion jointly shape BER–SNR under DCO-OFDM. Rather than rehash mode-specific behavior, we compress per-mode baselines and present an integrated view (Section 5.3), quantifying effects across flat, moderate, and highly dispersive channels, and using $SNR@BER = 10^{-3}$ as a compact performance metric (Section 5.1). Unless otherwise stated, all results use the configurations reported in Table 3.

5.1. BER Performance for PHY Modes

Figure 3 reports HT only and is used as a robust baseline under dispersive channels, given its longer effective guard and more conservative spectral usage. Accordingly, statements tied to this plot are HT-specific. As a quantitative reference, Table 4 provides the SNR required to reach $BER = 10^{-3}$ ($SNR@BER = 10^{-3}$) per PHY mode and data rate, which we use as baseline throughout. Within HT, the dynamic bias matches or slightly surpasses the static bias at a given BER while requiring a lower mean BCD (power proxy), whereas No-DCO (clipping) performs worse due to distortion (non-compliant). For flat/LOS conditions ($L = 1$), Table 5 shows that dynamic is ≈ 0.7 dB better than static at $BER = 10^{-3}$.

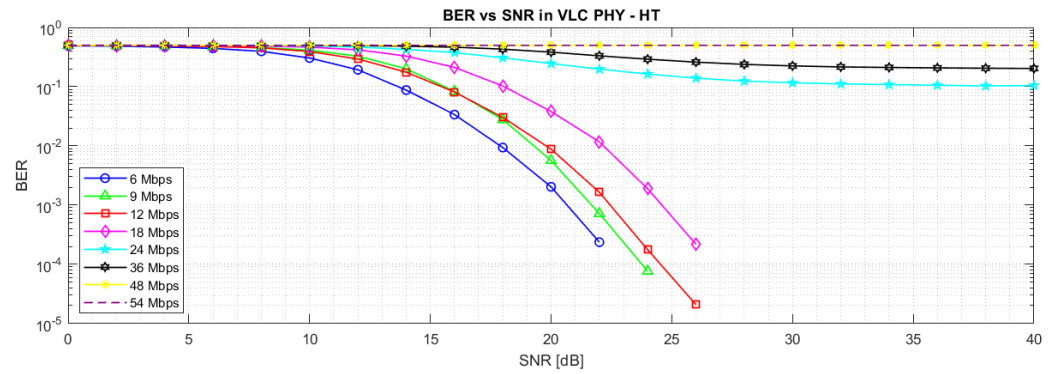


Figure 3. BER vs. SNR for IEEE 802.11bb PHY-HT mode in VLC.

Table 4. SNR required to achieve $BER = 10^{-3}$ across PHY modes and data rates under DCO-OFDM.

Rate	HT	VHT	HE
6 Mbps	≈ 22	≈ 23.5	≈ 21.5
9 Mbps	≈ 24	≈ 25.5	≈ 23.5
12 Mbps	≈ 25.5	≈ 27.5	≈ 25.5
18 Mbps	≈ 27.5	≈ 28.5	≈ 26
24 Mbps	NR	NR	≈ 28.5
36 Mbps	NR	NR	≈ 31.5
48/54 Mbps	NR	NR	NR

Table 5. Optical channel and biasing configurations used for DCO-OFDM simulations [2,6,12].

Channel	Bias	SNR@ 10^{-3}
Flat (L = 1)	Dynamic	≈ 24
Flat (L = 1)	Static	≈ 24.7
Moderate (L = 3)	Static	≈ 27.5
Moderate (L = 3)	Dynamic	≈ 28.5
Dispersive (L = 5)	Static	≈ 31.5
Dispersive (L = 5)	Dynamic	≈ 35
Dispersive, Flat, Moderate	No-DCO (clipping)	NR

Figure 4 (VHT) shows higher throughput than HT at the cost of a moderate robustness penalty; under moderate dispersion it remains competitive given sufficient SNR and careful bias selection. Figure 5 (HE) attains the highest rates but is more sensitive as the delay spread approaches the CP, which steepens its BER slope in dispersive channels. As shown in Section 5.1, static bias tends to recover several dB at BER targets; consistently, Table 5 indicates that static reduces the SNR required for $BER = 10^{-3}$ by ≈ 3.5 dB versus dynamic in dispersive conditions, and that HE incurs the largest SNR penalty as the delay spread nears the CP. The Δ SNR between dynamic and static across scenarios is summarized in Table 6.

Table 4 provides SNR@ $BER = 10^{-3}$ baselines per PHY mode and bitrate. When the channel delay spread approaches the CP, HE demands higher SNR (throughput-oriented design), HT remains more robust (at lower throughput), and VHT lies in between. These baselines contextualize the biasing effects discussed next (Tables 5 and 6).

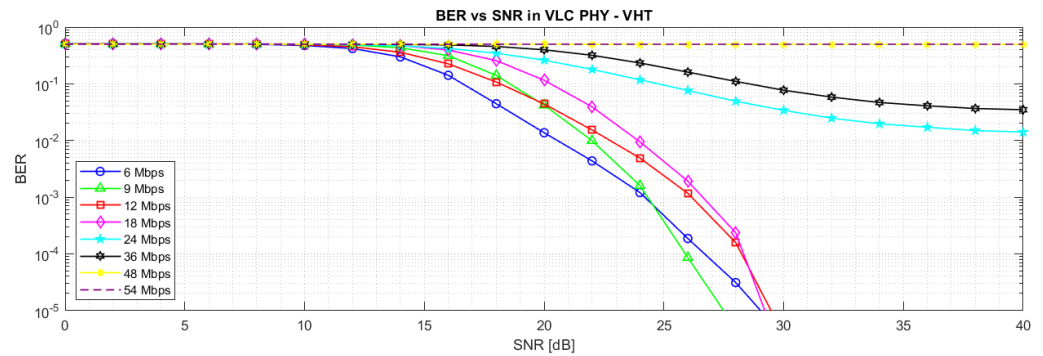


Figure 4. BER vs. SNR for IEEE 802.11bb PHY-VHT mode in VLC.

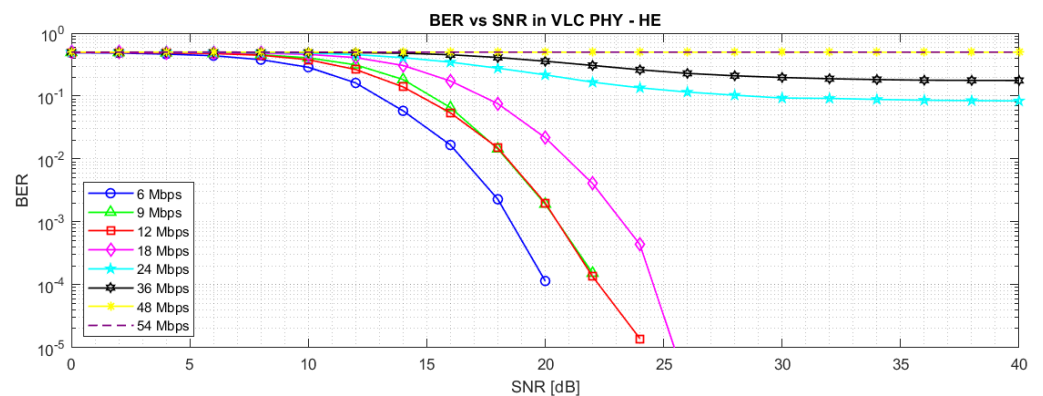


Figure 5. BER vs. SNR for IEEE 802.11bb PHY-HE mode in VLC.

Table 6. Comparative SNR gap (Δ SNR) between dynamic and static biasing across optical channel dispersion scenarios.

Channel	Δ (SNR) = Dynamic – Static
Flat (L = 1)	≈ -0.7 dB (Dynamic is better)
Moderate (L = 3)	≈ 1 dB (Static is better)
Dispersive (L = 5)	≈ 3.5 dB (The static is clearly superior)

5.2. Joint Impact of Biasing and Channel Dispersion

This subsection integrates all scenarios and quantifies the combined effect of DC-biasing strategies (static, dynamic, no-DCO/clipping) and optical channel dispersion ($L = 1/3/5$ taps). We report $\text{SNR@BER} = 10^{-3}$, defined as the minimum SNR at which the BER first falls below 10^{-3} ; when the curve does not cross, the entry is marked “—”. Findings are consistent across HT/VHT/HE, with differences in magnitude due to each mode’s pilot density, FFT size, and effective CP.

In flat/LOS channels ($L = 1$), dynamic bias can match or slightly surpass static bias because it trims surplus DC on a per-symbol basis, improving power efficiency without harming BER at sufficient SNR. As dispersion increases ($L = 3/5$), static bias becomes consistently superior, reducing the SNR required to reach BER targets by providing additional headroom against ISI with respect to the CP. No-DCO (clipping) produces the worst BER due to nonlinear distortion and is not recommended for data links. For $L = 1$, the dynamic bias requires ≈ 24 dB whereas static requires ≈ 24.7 dB at $\text{BER} = 10^{-3}$ (see Table 5), hence $\text{dynamic} \geq \text{static}$ under flat/LOS conditions.

Table 5 summarizes $\text{SNR@BER} = 10^{-3}$. Two patterns emerge: (i) $\text{dynamic} \geq \text{static}$ for $L = 1$, especially in VHT/HE at high SNR; (ii) $\text{static} > \text{dynamic}$ for $L = 3/5$, with the largest gains under HE where the CP margin is tight. These trends yield concrete guidance for

802.11bb VLC transmitters: choose dynamic bias in near-flat channels to save DC power; switch to static bias in dispersive rooms to preserve BER at lower SNR.

5.3. HE Mode Sensitivity to Noise and Dispersion

Figure 6 isolates HE because it prioritizes spectral efficiency and operates with tighter GI/CP than HT/VHT, making it the most dispersion-sensitive PHY. When the channel delay spread approaches the CP, the effective margin shrinks, and residual ISI steepens the BER curves; this effect is stronger at higher modulations/coding rates and with pilot patterns optimized for efficiency. In flat/LOS conditions ($\tau_{rms} \ll T_{CP}$), a dynamic bias avoids surplus DC and slightly reduces the SNR required at a given BER; as dispersion increases ($L = 3/5$), the additional DC margin provided by static bias better mitigates ISI, shifting the BER curve to lower SNR. Consistently, HE tends to demand higher SNR than HT/VHT to reach the same BER in dispersive channels, while excelling in flat links where throughput is prioritized. Operationally, prefer static bias in moderately/highly dispersive rooms and dynamic bias in flat/high-SNR links. These trends are quantified by the $\Delta(\text{SNR})$ entries in Table 6.

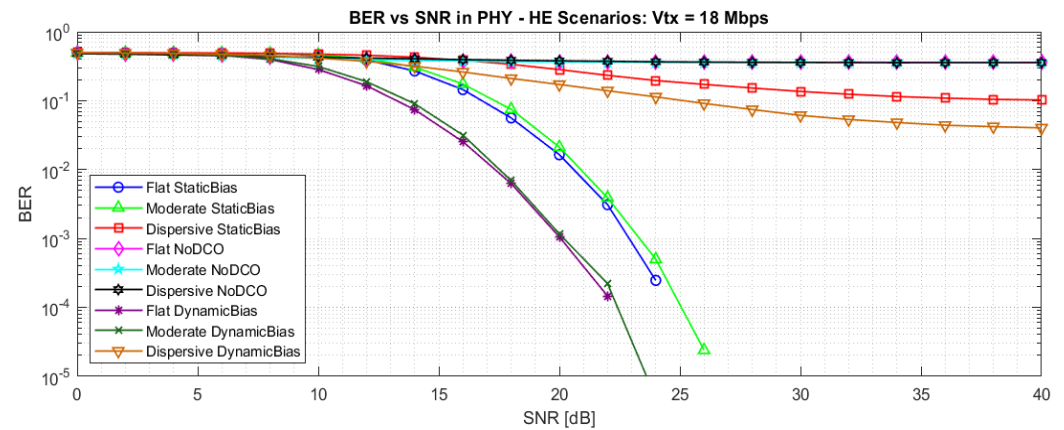


Figure 6. BER vs. SNR for IEEE 802.11bb PHY-HE mode at 18 Mbps under different conditions.

Table 6 operationalizes the biasing trade-off via $\Delta\text{SNR} = \text{SNR}_{\text{dyn}} - \text{SNR}_{\text{static}}$: (i) in flat channels ($L = 1$), dynamic saves ≈ 0.7 dB; (ii) with moderate dispersion ($L = 3$), static is ≈ 1 dB better; (iii) under high dispersion ($L = 5$), static is clearly superior by ≈ 3.5 dB. Practically, use dynamic in LOS/flat, and use static in dispersive rooms.

6. Conclusions

This study provided a standard-compliant assessment of DCO-OFDM for VLC under the IEEE 802.11bb PHY modes (HT, VHT, HE), focusing on how DC-biasing strategies and optical channel dispersion jointly shape BER versus SNR. Rather than introducing a new analytical model, the work delivers a practical, standardized evaluation that clarifies when static or dynamic biasing is preferable and how the delay spread relative to the cyclic prefix (CP) influences robustness across modes. The results indicate that, in flat/LOS channels, dynamic bias can match or slightly surpass static bias by avoiding surplus DC and improving power efficiency at sufficient SNR; in moderately to highly dispersive channels, static bias proves more robust, requiring lower SNR to meet a target BER because the added DC margin mitigates ISI with respect to the CP. Across modes, HT exhibits the highest robustness in dispersive conditions, while VHT/HE deliver greater throughput at the expense of higher SNR and greater sensitivity when the channel delay spread approaches the CP. From an implementation standpoint, static bias requires a single per-packet variance (σ_x) estimate and a fixed DC addition with simple control, whereas dynamic

bias estimates σ_x per symbol and updates the BCD in real time, adding only moderate overhead relative to IFFT/FEC; consequently, dynamic bias is attractive in flat/high-SNR links for power efficiency (lower mean BCD), whereas static bias is preferable in dispersive channels where robustness dominates power savings. Overall, these findings translate into actionable design guidance within the 802.11bb framework: favor dynamic bias in LOS/flat scenarios with ample SNR (especially for VHT/HE), prefer static bias under dispersion (notably with HT when robustness is paramount), and avoid clipping (No-DCO) due to the associated distortion and BER penalty. Future work will investigate hybrid biasing that switches between dynamic and static modes according to channel conditions, extend the analysis to LED nonlinearity and PAPR, and pursue hardware validation under 802.11bb-compliant operation.

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Abbreviations

BER	Bit Error Rate
DCO	Direct Current-biased Optical Orthogonal
IFFT	Inverse Fast Fourier Transform
IM/DD	Intensity Modulation/Direct Detection
QAM	Quadrature Amplitude Modulation

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