Engineering Advances, 2026, 6(1), 31-35
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

System Performance Evaluation Principle of Heterogeneous Optical Devices in Parallel Use

Zichen Zhao

Hebei University, Baoding 102600, Hebei, China.

How to cite this paper: Zichen Zhao. (2026) System Performance Evaluation Principle of Heterogeneous Optical Devices in Parallel Use. *Engineering Advances*, 6(1), 31-35.
DOI: 10.26855/ea.2026.03.007

Received: December 30, 2025
Accepted: January 27, 2026
Published: February 26, 2026

***Corresponding author:** Zichen Zhao, Hebei University, Baoding 102600, Hebei, China.

Abstract

In high-speed optical communication, Visible Light Communication (VLC), optical interconnection, and optical sensing systems, heterogeneous optical device parallel architectures (e.g., hybrid networks combining different wavelength LEDs/lasers, photoelectric detectors, and modulation bandwidth light sources) are commonly adopted to overcome limitations in bandwidth, power, response speed, and cost of single optical components. While such architectures significantly enhance system capacity, coverage, and reliability, they also introduce challenges, including channel asymmetry, interference coupling, delay differences, and device characteristic mismatches, which directly impact overall system performance. This paper systematically analyzes the primary contradictions and performance-influencing factors in heterogeneous optical device parallel applications, based on optical communication theories and characteristics of various heterogeneous devices. It proposes quantifiable and actionable system performance evaluation criteria encompassing multiple dimensions such as rate capacity, reliability, delay synchronization, energy consumption, and anti-jamming compatibility. The study provides specific evaluation metrics, threshold values, and engineering implementation procedures, offering theoretical foundations and practical guidance for planning, selection, deployment, and optimization of heterogeneous optical device parallel systems.

Keywords

Heterogeneous Optical Devices; Parallel Utilization; System Performance; Judgment Principles; Optical Communication

1. Introduction

With exponential growth in demands for communication speed, connection density, and reliability across 5G/6G networks, data centers, and industrial internet applications, single optical components (e.g., traditional LEDs, PIN-PD, and narrowband lasers) can no longer meet the system's comprehensive requirements for bandwidth, power efficiency, response speed, and cost. The parallel deployment of heterogeneous optical devices has emerged as a pivotal solution to overcome performance bottlenecks. For instance, VLC systems utilize GaN Micro-LEDs and blue LEDs in parallel to boost transmission rates, while optical receivers employ PIN-PD and APD to balance sensitivity and dynamic range. In optical interconnects, wavelength division multiplexing (WDM) and space division multiplexing (SDM) are achieved through parallel deployment of lasers with different wavelengths.

However, due to inherent differences in modulation bandwidth, response wavelength, optical power output, noise characteristics, and delay characteristics among heterogeneous optical devices, parallel operation may lead to channel asymmetry, interference superposition, synchronization misalignment, and power consumption imbalance. The absence of scientific and rational performance evaluation principles often results in "1+1<2" scenarios or even performance degradation. Current research predominantly focuses on single heterogeneous device combinations for performance enhancement, lacking a unified and systematic performance evaluation framework to guide practical engineering applications in device selection and system design. Addressing the engineering demands of heterogeneous optical device parallel systems, this paper systematically identifies core performance influencing factors, establishes multidimensional evaluation principles, and defines clear assessment metrics, quantified thresholds, and evaluation procedures. These findings provide theoretical support and practical guidance for performance evaluation, solution selection, and iterative optimization of heterogeneous optical device parallel systems.

2. Core Characteristics and Performance Influencing Factors of Parallel Use of Heterogeneous Optical Devices

2.1 Core Characteristics of Heterogeneous Optical Devices in Parallel

The key to parallel application of heterogeneous optical devices lies in "differential complementarity and collaborative operation," characterized by three essential features: First, asymmetric device properties, where different optical devices exhibit distinct modulation bandwidth (Δf), optical power (P), response wavelength (λ), noise figure (NF), and delay (τ). Second, coordinated operational modes, employing spatial division multiplexing (SDM), wavelength division multiplexing (WDM), code division multiplexing (CDM), or hybrid multiplexing techniques. Third, parallel transmission of multiple devices to enhance system capacity. Lastly, system performance coupling, where performance defects in individual devices propagate along parallel links, creating a "bottleneck effect," while inter-device interference and synchronization issues further degrade overall system performance [1].

2.2 Core Performance Influencing Factors

2.2.1 Device parameter mismatch

The different modulation bandwidths cause the rate imbalance of different links, the imbalance of optical power causes the imbalance of receiving SNR, the overlapping of response wavelengths causes crosstalk, and the imbalance of delay causes ISI and synchronization error.

2.2.2 Link interference coupling

The optical crosstalk (e.g., radiation overlap of adjacent LEDs), electrical crosstalk (e.g., electromagnetic interference of driver circuit), and intersymbol interference (e.g., symbol overlap of different rate links) between parallel links will reduce the BER performance of the system.

2.2.3 Synchronization and timing deviation

The differences in driving delay, transmission delay, and processing delay of heterogeneous devices cause timing deviations (Δτ) between parallel links. If these deviations exceed the synchronization tolerance range, they may lead to data frame misalignment and demodulation failure.

3. Principle System for Performance Evaluation of Heterogeneous Optical Devices in Parallel Systems

3.1 Principles for Rate and Capacity Determination: Equal Emphasis on Equilibrium and Upper Limit

As primary performance metrics for heterogeneous optical device parallel systems, rate and capacity evaluation must balance single-link rate uniformity with overall system capacity limits to prevent both "bottleneck effects" and "resource wastage". Key evaluation indicators include: Single-link rate uniformity (γ), total system capacity utilization R_i/R_imax(η), and spectral efficiency (SE). The ratio of actual rate R_i to theoretical maximum rate R_imax (γ) should satisfy γ≥0.8 to avoid rate bottlenecks caused by parameter mismatches (γ<0.8). Link rates should be adjusted through modulation order, bandwidth balancing, and power compensation. Total system capacity (R_total) must exceed 0.9×ΣR_i, ensuring η≥90% to prevent insufficient parallel gain from interference, synchronization, or scheduling issues. For MIMO or WDM systems, spectral efficiency SE should reach at least 1.5 times the performance of the best-performing single device, demonstrating the capacity advantage of heterogeneous parallel systems. Link rates should align with service demands: high-bandwidth services (e.g., 8K video) should prioritize high-bandwidth devices, while low-rate services (e.g., sensor data) should use low-bandwidth devices to avoid resource wastage from "using oversized equipment for small tasks" [2].

3.2 Principle of Reliability and Stability: Dual Constraints of Bit Error Rate and Long-term Stability

Reliability and stability are critical for the engineering implementation of heterogeneous optical device parallel systems. Evaluation criteria should be based on BER compliance and long-term performance drift to ensure stable system operation in harsh environments. Key metrics include $BER_avgBER_avgA_avg$ average bit error rate (BER_avg), link availability (A), and performance drift rate (ΔP/Δt). Under nominal operating conditions (25°C, 50% humidity, background light interference ≤1e-6 (low-speed) / BER_avg ≤1e-9 (high-speed/long-distance) at 50 lux), critical services (≤1e-12 with single-link BER ≤1e-6) must prevent system-wide failure due to single-link failures (e.g., industrial control, medical applications). Parallel links should maintain ≥99.99% availability (A_i = uptime/total time) with at least one redundant link. When a link fails, the system must automatically switch to the redundant link without exceeding 30% total capacity reduction to ensure uninterrupted service. After 72 hours of continuous operation, the drift rate of key performance metrics (total capacity, BER, SNR) should remain ≤5% (ΔP/Δt), indicating performance degradation ≤5% from baseline. If the drift rate exceeds 5%, investigate potential causes such as device heat dissipation, driver voltage fluctuations, or optical power attenuation to optimize system stability.

3.3 Delay and Synchronization Judgment Principle: Controllable Time Difference and End-to-End Delay

In heterogeneous optical device parallel systems, latency and synchronization critically determine user experience for real-time applications (e.g., VR/AR, cloud gaming, industrial control). The evaluation $\Delta\tau T_e 2e\Delta\tau\Delta\tau \leq 0.1 \times Ts\Delta\tau \leq 10\%$criteria should ensure both temporal deviation within tolerable limits and end-to-end latency meeting service requirements. Key parameters include inter-link time offset (Δτ), end-to-end latency (T), and synchronization setup time (T_sync). For OFDM systems, the inter-link time offset (Ts, measured in symbol time) must comply with the CP length. When Δτ exceeds tolerance thresholds, delay compensation techniques (Delay Line or Clock Synchronization) should be employed to maintain it within acceptable ranges, thereby eliminating intersymbol crosstalk and frame offsets.

Delay metrics are classified by service type: real-time services ($T_e 2eT_e 2eT_e 2eT_s yncT_s ync \leq 1ms$VR/AR, industrial control) require ≤10 ms, HD video services ≤50 ms, and general data services ≤100 ms. Parallel operations across heterogeneous devices must not introduce additional latency, with end-to-end latency not exceeding 1.2 times that of a single optimal device system. During system restarts or link switching, synchronization recovery time () must meet requirements to ensure rapid service restoration. For dynamic heterogeneous parallel systems (e.g., real-time link adjustments), synchronization recovery time should be ≤0.5 ms to prevent data loss caused by synchronization delays.

3.4 Principles of Power Consumption and Cost Evaluation: Optimal Energy Efficiency and Cost-Performance Balance

Power consumption and cost constraints limit the commercialization of heterogeneous optical device parallel systems. The evaluation criteria prioritize optimal energy efficiency ratio (η_p) and balanced system cost-performance $R_t otal/P_t otalC_t otal/R_t otal\xi\eta_p P_t otal/R_t otal\eta_p >= 1Gbps/W\eta_p >= 100Mbps/W\xi = P_i/P_a vg \leq 1.5C_p \leq 1.2 \times C_s ingle$ratio ($C_p$), requiring parallel systems to avoid unsustainable development models characterized by "high performance, high power consumption, and high cost." Key evaluation parameters include: system energy efficiency ratio (η_p=), unit capacity cost (C_p=), and power consumption balance. The energy efficiency ratio (η_p=) must satisfy (for high-speed systems) or (for low-speed systems), and should not be lower than that of a single optimal device system. Otherwise, energy efficiency optimization can be achieved through low-power devices and dynamic scheduling of low-power devices, such as disabling idle links. The power consumption (P_i) of each parallel device should meet (where P_avg is the average power consumption) to prevent excessive local device power consumption from causing thermal stress and performance drift. For high-power devices (e.g., LD), independent cooling modules must be provided to ensure power consumption and heat dissipation compatibility. The unit capacity cost (C_p) should meet (where C_single is the unit capacity cost of a single optimal device system), meaning the cost increase for heterogeneous parallel systems should not exceed 20%, while capacity improvement should be no less than 50%. Priority should be given to "high-cost-performance heterogeneous combinations" (e.g., Micro-LED + low-cost PIN-PD) to avoid cost overruns caused by blindly adopting high-end devices [3].

3.5 Principles for Interference Resistance and Compatibility Assessment: Compliance with Interference Suppression Standards and Cross-Scenario Compatibility

Since heterogeneous optical parallel systems are susceptible to optical crosstalk, electrical interference, and environmental disturbances (background light, temperature), the evaluation criteria must ensure sufficient interference suppression capability and cross-scenario compatibility to enhance system adaptability. Key metrics include Crosstalk Suppression Ratio (ICR), Environmental Interference Tolerance (ΔE), and Protocol Compatibility (C_p). For parallel channels, the ICR for optical and electrical crosstalk must be ≥30dB, meaning crosstalk power should remain below 1/1000 of the signal power [4]. In WDM parallel systems, adjacent wavelength channels require an ICR ≥40dB to prevent crosstalk degradation caused by wavelength overlap. When ICR <30dB, measures like optical filtering, electrical shielding, and spatial isolation should be implemented to improve crosstalk suppression. Under temperature variations (-10℃~60℃), humidity changes (30%~90%), and background light interference (0~1000 lux), the system's core performance indicators (BER, R_total) must show ≤10% rate of change, ensuring ΔE ≥90%. For outdoor or industrial environments, ΔE ≥95% is required to guarantee stable operation in harsh conditions. Heterogeneous parallel systems should support mainstream optical communication protocols (e.g., IEEE 802.11bb VLC, 5G NR, Ethernet Optical Interconnect) and adapt to diverse scenarios (indoor/outdoor, industrial, data center). During scenario switching (e.g., transitioning from indoor VLC to outdoor optical communication), performance degradation should not exceed 20%, demonstrating strong compatibility and adaptability [5].

4. Performance Evaluation Process and Engineering Application of Heterogeneous Optical Devices in Parallel Systems

4.1 Standardized Assessment Process

To achieve quantified, efficient, and standardized performance evaluation of heterogeneous optical device parallel systems, we established a four-step validation process: "parameter acquisition → metric calculation → criterion matching → optimization iteration". The system collects core device parameters (modulation bandwidth, optical power, delay, power consumption), operational parameters (total capacity, BER, delay, crosstalk ratio), and environmental parameters (temperature, humidity, interference intensity), ensuring comprehensive coverage of both nominal and extreme operating conditions. Based on collected parameters, we calculate key evaluation metrics, including rate balancing, capacity utilization, average BER, timing deviation, energy efficiency ratio, and ICR, while maintaining calculation accuracy and consistency [6]. These metric values are then mapped to the five-dimensional evaluation criteria proposed in this study, with non-compliance flags marked and root causes identified (device mismatch, interference exceedance, synchronization deviation). For non-compliant items, targeted improvement measures are implemented (e.g., component selection, algorithm adjustment, synchronization method modification, thermal design optimization), followed by iterative testing until full compliance is achieved. All metrics must meet the established evaluation standards.

4.2 Engineering Application Cases

Taking the heterogeneous optical device parallel system integrating VLC+5G (GaN Micro-LED+blue light LD parallel emission, PIN-PD+APD parallel reception) as an example, the performance verification is conducted using the evaluation principles outlined in this paper. The single-link rate equalization γ=0.85 (≥0.8), total capacity utilization η=92% (≥90%), and spectral efficiency $A_avg = 99.995\%$（$\geq 99.99\%$）$C_\mathrm{p} = 1.1 \times C_single$（$\leq 1.2 \times C_single$）SE=85 bps/Hz (1.8 times that of a single Micro-LED system) meet the rate and capacity evaluation criteria. Reliability and stability assessments show BER_avg=8.5×10^{-7} ($\leq10^{-6}$), link availability, and 72-hour performance drift rate ΔP/Δt=3.2% (≤5%), satisfying the reliability and stability evaluation principles. For latency and synchronization, the timing deviation Δτ=0.08×T_s (≤0.1×T_s), end-to-end latency T_e2e=6.8 ms (≤10 ms), and synchronization recovery time T_sync=0.6 ms (≤1 ms) meet the latency and synchronization evaluation criteria. Power efficiency and cost evaluation demonstrate an energy efficiency ratio η_p=1.2 Gbps/W (≥1 Gbps/W), power balance ξ=1.3 (≤1.5), and unit capacity cost, fulfilling the power and cost evaluation principles. Interference resistance and compatibility assessments reveal a crosstalk suppression ratio ICR=35 dB (≥30 dB), environmental interference tolerance ΔE=93% (≥90%), and compatibility with VLC IEEE 802.11bb and 5G NR protocols, satisfying the interference resistance and compatibility evaluation principles. The results show that all the indexes of the parallel system of the optical device meet the criterion of this paper, and the system performance meets the requirements of engineering application, which proves the feasibility and practicability of the criterion [7].

5. Conclusion

Parallel utilization of heterogeneous optical devices represents a breakthrough in overcoming performance bottlenecks in optical communication systems, while scientific and systematic performance evaluation principles serve as prerequisites for ensuring engineering applications. This paper proposes a five-dimensional framework for performance evaluation criteria based on the inherent characteristics of heterogeneous optical devices and the engineering requirements of parallel systems. The framework encompasses five dimensions: rate and capacity, reliability and stability, latency and synchronization, power consumption and cost, as well as anti-interference and compatibility. It defines key evaluation parameters, numerical thresholds, and standardized evaluation procedures, with the effectiveness validated through engineering case studies. This criterion system balances theoretical rigor with practical applicability, providing performance evaluation metrics for parallel applications of diverse light source devices while serving as practical guidance for device selection, system design, and optimization upgrades [8]. Future work should focus on supplementing extreme-case evaluation, real-time online assessment, and intelligent decision-making capabilities, alongside standardization and industrial promotion. These efforts will lay the foundation for the large-scale commercialization of heterogeneous optical device parallel technology in 5G/6G networks, data centers, and industrial internet applications.

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