Segmented Power Optimization for Achieving 800 Gbps Per-Channel Transmission in C+L+S Band Fiber Systems

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***Abstract*—Ultra-wideband optical transmission systems operating over the C+L+S bands are critical for meeting the growing demand for high-capacity networks. However, existing power optimization strategies—typically based on coarse control using one slope and one offset per band—struggle to achieve sufficiently flat SNR profiles, especially in the L-band. To address this limitation, we propose a segmented power allocation approach that models the L-band power distribution as multiple linear segments, each controlled by offset and slope parameters. Using particle swarm optimization (PSO) under the ISRS GN model, we evaluate various segmentation strategies in a 181-channel, 20 THz WDM system targeting 800 Gbps per-channel transmission. Experimental results demonstrate that segmenting the L-band into three or four regions significantly reduces SNR ripple to below 0.2 dB, improves minimum achievable data rate to over 797 Gbps, and maintains acceptable optimization time, offering a superior trade-off between performance and complexity.**

***Index Terms*—C+L+S-band transmission, launch power optimization, 800Gbps, GSNR flatness, optical network**

I. Introduction

The explosive growth of emerging 5G applications, especially those propelled by artificial intelligence services, has placed unprecedented demands on network capacity. The optical network field is actively seeking transformative solutions to meet the soaring demand for massive data exchange and real-time processing. One of the primary strategies involves enhancing capacity by leveraging the unused low-loss bands within currently deployed fiber networks [1]. The C+L+S band transmission system has garnered widespread attention for its potential to enhance system capacity significantly.

However, in C+L+S band systems, inter-channel stimulated Raman scattering (ISRS) becomes more pronounced across the extended band, leading to substantial power transfer between channels. This phenomenon complicates the estimation of nonlinear interference (NLI), as the interaction between ISRS and fiber attenuation induces varying distortions among optical channels [2]. Consequently, the overall transmission performance of C+L+S band systems is critically dependent on the accurate allocation of launch power for each channel.

Recent studies have increasingly adopted advanced optimization algorithms, such as Particle Swarm Optimization (PSO) and Simulated Annealing (SA), to address the problem of channel power allocation in C+L+S band transmission systems. These efforts have predominantly focused on two fundamental objectives: (1) maximizing total system capacity [3], [4], and (2) equalizing the generalized signal-to-noise ratio

(GSNR) across all transmission channels [5], [6]. In some cases, optimization strategies have been proposed to jointly consider both objectives, aiming to improve transmission performance in a comprehensive and balanced manner [7], [8].

In this paper, we focus on optical power optimization for 100 × 8 km C+L+S band long-haul transmission systems. The system is designed to support high data rates of 800 Gbps per channel. Conventional approaches to power allocation typically employ six optimization variables, corresponding to the slope and offset of the power distribution in each band. We propose an enhanced strategy that segments the L-band and continues to use slope and offset values as optimization variables. By introducing a small number of additional variables, the proposed method can achieve a target SNR with the ripple less than 0.2 dB while maintaining high optimization efficiency.

II. MOTIVATION

A flattened GSNR profile across WDM channels plays a critical role in simplifying lightpath provisioning and resource management in optical network. Various power optimization strategies have been explored to improve GSNR uniformity while maintaining computational efficiency. The general optimization methods choose the slope and offset of the channel power distribution in each band as the optimization variables to maintain a balance between system performance and computation time [1], [7]. These methods are particularly attractive due to their low-dimensional nature, which significantly reduces the computational burden and facilitates rapid convergence in practical deployments.

However, this low-dimensional parameterization exhibits limitations when the optimization goal shifts toward achieving stringent GSNR flatness, particularly under high data rate scenarios such as 800 Gbps per channel. The reduced parameter space limits the ability to capture finer spectral variations in GSNR, leading to suboptimal results in wideband systems. In such cases, the slope-and-offset model may not provide sufficient flexibility to account for the nonlinear characteristics introduced by effects such as ISRS. Conversely, treating each channel power as an independent optimization variable can significantly enhance GSNR flatness. However, traditional evolutionary algorithms, such as PSO, are highly susceptible to the curse of dimensionality, which significantly increases the search space complexity and leads to prohibitive computational costs.

We conducted experiments on a C+L+S band transmission system covering a total modulation bandwidth of 20 THz, ranging from 1464.8 nm to 1623.3 nm. The system includes 181 WDM channels across 100 × 8 km fiber spans, and the optimization target is GSNR flatness at a per-channel data rate of 800 Gbps. Two distinct variable configurations were evaluated using PSO: (1) a full-channel optimization with 181 power variables, and (2) a slope-and-offset model with 6 variables (2 per band). The objective function of the optimization is set as shown in (1).

$$f = (\mathbf{SNR}_{800G} - \mathbf{SNR})^\top (\mathbf{SNR}_{800G} - \mathbf{SNR}) \tag{1}$$

As shown in Table I, the full-channel optimization achieves exceptional GSNR flatness, with a ripple as low as 0.006 dB, and a minimum channel data rate of 799.8 Gbps, which is nearly ideal for the 800 Gbps target. However, this method incurs extremely high computational complexity due to the dimensionality of 181 variables, resulting in an optimization time of 76,582 seconds. In contrast, the slope-and-offset model significantly reduces the number of variables to only six, achieving a much faster convergence with an optimization time of just 283 seconds, approximately 270 times faster than the full-channel approach. Despite this efficiency, the slope-and-offset model yields a considerably larger GSNR ripple of 1.048 dB, and the minimum channel data rate drops to 757.2 Gbps, falling short of the transmission target. These results highlight the trade-off between optimization accuracy and computational cost under different modeling strategies.

TABLE I
SNR RIPPLE, MINIMUM DATA RATE, AND RUNTIME: FULL-CHANNEL VS. SLOPE-OFFSET OPTIMIZATION

Dimension	**SNR Ripple** (dB)	**min *data rate*** (Gbps)	**Time** (s)
181	0.006	799.8	76582
6	1.048	757.2	283

Further analysis of the optimized launch power and SNR profiles (Fig. 1) reveals that both approaches yield similar power distributions across the C and S bands, which appear approximately linear. This suggests that, in the C+S band, the optimal power distribution in the C+S band conforms to a linear trend, so the slope and offset of power can be used as optimization variables. In contrast, the L band exhibits substantial discrepancies between the two methods, indicating that a linear assumption is inadequate for this band.

Motivated by these observations, we propose an improved power allocation model that partitions the L band into multiple segments, with each segment approximated by an independent linear distribution. The slope and offset of each segment are used as optimization variables, while the C and S bands retain their original two-parameter representations. The model captures essential spectral variations without treating each channel independently by tailoring a more refined piecewise-linear approximation to the L band. This approach introduces only a modest increase in variable count, avoiding the dimensionality explosion of full-channel optimization, while significantly improving SNR flatness and ensuring closer adherence to the target data rate in high-capacity scenarios such as 800 Gbps per channel.

III. SEGMENTATION METHOD AND RESULTS

To develop a more efficient optimization strategy for launch power allocation, we analyze the optimal power profile obtained by treating each WDM channel as an independent variable (as shown in Fig. 1). We perform piecewise linear fitting over the L-band portion of this profile, which contains 69 WDM channels, to identify suitable segmentation strategies.

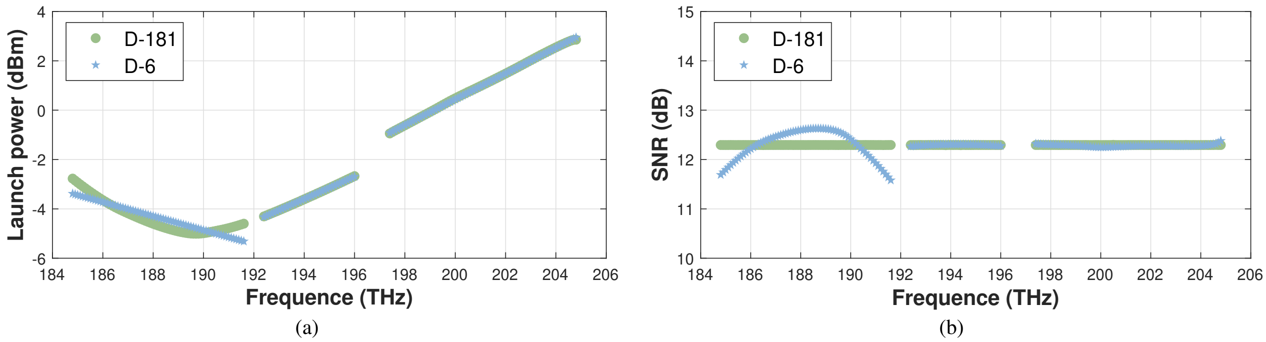


Fig. 1. Performance evaluation: Full-Channel vs. Slope-Offset Optimization
(a) optimized launch power profiles and (b) SNR per channel of optimized launch power

Three segmentation schemes are considered, in which the L-band is divided into 2, 3, and 4 segments, respectively. The specific channel indices corresponding to each segment are detailed in Table II.

TABLE II
GLOBAL VARIABLE DIMENSION UNDER DIFFERENT SEGMENTATION METHODS IN L-BAND

Dimension	Segment Point in L-band
6	[1:69]
8	[1:50], [51:69]
10	[1:20], [21:50], [51:69]
12	[1:15], [16:35], [36:50], [51:69]

The simulations are conducted on a C+L+S band system spanning from 1464.8 nm to 1623.3 nm, with a central reference wavelength at 1540 nm. To mitigate edge effects, the system includes a 10 nm S/C guard band and a 5 nm C/L guard band. In total, $N_{ch} = 181$ WDM channels are uniformly spaced at 100 GHz and modulated at a symbol rate of 96 GBd. System modeling is based on the closed-form ISRS Gaussian Noise (ISRS-GN) model [9], which involves numerically solving the Raman ordinary differential equations (ODEs) and applying nonlinear regression to fit wavelength-dependent model parameters. The amplifier noise figure is assumed to be flat within each spectral band, with values set to 6 dB for the S-band, and 5 dB for both the C- and L-bands.

All experiments were optimized using PSO on a machine with a 3.5 GHz 64-core CPU. The maximum number of iterations is set to 10^4, and the function tolerance is fixed at 10^{-8}.

Fig. 2 presents the optimized launch power distributions and corresponding SNR profiles under four scenarios: no segmentation of the L-band and segmentation into 2, 3, and 4 linear regions, respectively. Across all cases, the C and S bands exhibit highly consistent power and SNR profiles, suggesting that their optimal launch power inherently follows a quasi-linear distribution. In contrast, the L-band shows significant variation among the four configurations, indicating a more complex relationship between power allocation and SNR performance in this spectral region. These results imply that a simple linear assumption for the L-band may be inadequate to achieve uniform SNR performance.

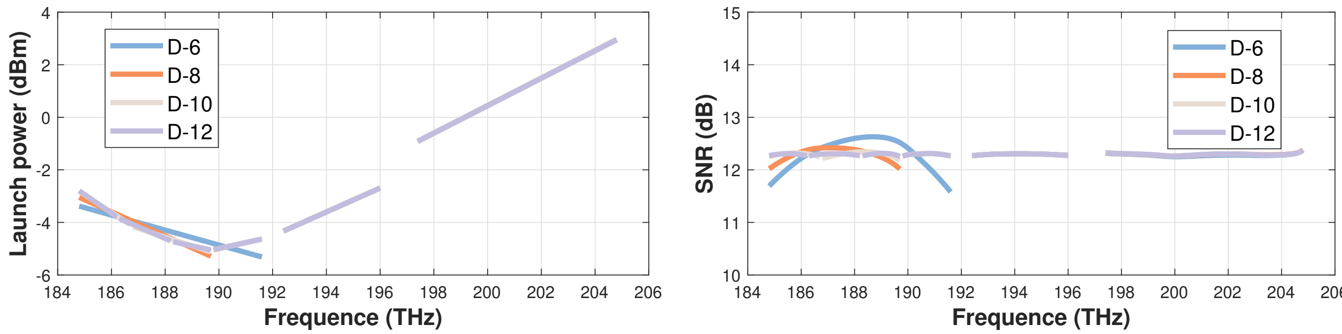
Fig. 3 presents comparative bar plots for SNR ripple, minimum channel capacity, and optimization run-time across the four scenarios. As shown in Fig. 3 (a), when the L-band is not segmented, the signal-to-noise ratio ripple is 1.048 dB. When divided into regions 2, 3 and 4, the ripples decreased to 0.274 dB, 0.199 dB and 0.124 dB, respectively. This downward trend clearly indicates that increasing the number of L-band segments leads to a smoother SNR profile. The ripple values of the 3-band and 4-band schemes are lower than 0.2 dB, which can be regarded as the standard of signal-to-noise ratio flatness in high-performance systems. Fig. 3 (b) shows the minimum achievable per-channel transmission rate across all WDM channels. Without segmentation, the lowest rate is 757.2 Gbps, which is far below the target of 800 Gbps. With 2, 3, and 4 segments, the minimum capacity increases to 783.4 Gbps, 793.2 Gbps, and 797.7 Gbps, respectively. These results demonstrate that increasing segmentation not only flattens the SNR profile but also ensures more channels meet or approach the target capacity.

Fig. 3 (c) evaluates the computational efficiency of each scheme. The total runtime for the four cases is 283 s, 485 s, 579 s, and 635 s, respectively. While runtime increases with the number of segments due to the higher dimensionality of the optimization space, the growth remains within acceptable bounds. The time is substantially lower than that incurred by the full per-channel optimization approach.

These findings demonstrate that segmenting the L-band into multiple linear regions offers a favorable trade-off between performance and complexity. By introducing only a modest increase in the number of variables, the approach circumvents the curse of dimensionality while significantly enhancing SNR flatness and system throughput.

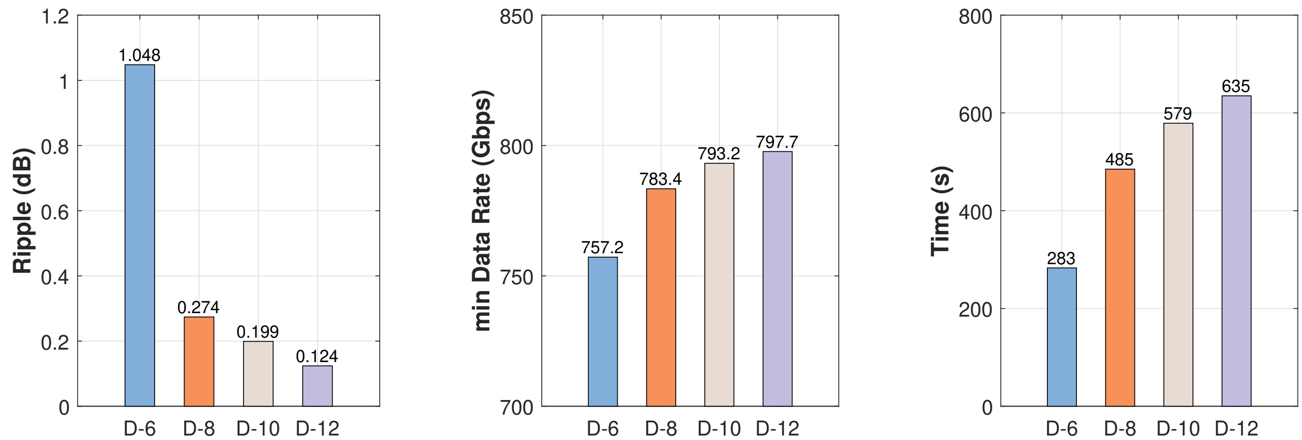
IV. CONCLUSION

In this work, we investigated a refined channel power optimization strategy for ultra-wideband C+L+S optical systems targeting flat SNR profiles under 800 Gbps per-channel transmission. While traditional methods optimize power using a single slope and offset per band to balance performance



(a) (b)

Fig. 2. Performance evaluation of four segmentation methods:(a) optimized launch power profiles and (b) SNR per channel of optimized launch power



(a) (b) (c)

Fig. 3. The comparison of (a) SNR ripple, (b) minimum data rate, (c) computational time among four segmentation methods.

and complexity, our results show this approach struggles to achieve sufficient flatness, particularly in the L-band. To overcome this limitation, we proposed segmenting the L-band into multiple linear regions, each described by its offset and slope, thereby introducing a small number of additional variables. This segmentation enables more accurate modeling of the optimal power profile while avoiding the dimensionality issues associated with per-channel optimization. Through simulations based on the ISRS GN model and PSO, we showed that dividing the L-band into four segments reduces the SNR ripple from 1.048 dB to as low as 0.124 dB. Simultaneously, the minimum channel data rate increases from 757.2 Gbps to 797.7 Gbps, approaching the 800 Gbps target. Despite the increase in variable dimension, the optimization time remains within an acceptable range, significantly lower than that of full per-channel optimization. These results validate the effectiveness and practicality of our proposed method for enhancing transmission performance in long-haul multi-band optical systems.

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