SNR optimization of multi-span dispersion management systems in single channel condition A study of power and number of span effects

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***Abstract*—This report presents a comprehensive analysis of the signal-to-noise ratio (SNR) in a dispersion-managed optical link, focusing on the influence of key physical parameters such as transmitted power and span count. The study examines the degradation of SNR due to fiber impairments, including nonlinear effects, dispersion, and amplified spontaneous emission (ASE) noise. By varying the optical power and the number of spans in the system, we calculate and model the relationship between SNR and the product of power and span count (η = P * N). The findings are supported by two sets of simulations: SNR versus power for different span numbers, and SNR versus η. The results demonstrate a clear non-linear behavior between η and SNR, with the SNR increasing at low η values and decreasing beyond an optimal power-span product. These results offer insights into the optimal power levels and span configurations to minimize fiber impairments such as nonlinearity, dispersion, and amplified spontaneous emission (ASE) noise.**

I. Introduction

Optical fiber links periodically amplified by Erbium doped fiber amplifiers (EDFAs) are one of the fundamental building blocks of telecommunication networks and are thus a key enabler of our digital society. In long-haul optical communications, managing dispersion is vital to mitigate signal impairments that accumulate over extended distances. Dispersion-managed (DM) systems, which periodically compensate for chromatic dispersion, are particularly effective in preserving signal integrity in coherent transmission links. In DM systems, nonlinear interference (NLI) effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), accumulate due to high power levels and the number of spans, further compounded by amplified spontaneous emission (ASE) noise introduced by optical amplifiers like erbium-doped fiber amplifiers (EDFAs). The Gaussian nonlinear model (GNM) and related studies show that carefully managing power and span configurations can optimize the signal-to-noise ratio (SNR) across various link conditions, enhancing transmission performance. This report investigates the SNR behavior in a DM system as a function of η, the product of transmitted power (P) and the number of spans (N_{span}). The study aims to identify optimal power and span configurations to achieve high SNR with minimal nonlinear impairment, offering insights for efficient long-distance transmission design.

II. Theory

Modeling and optimization of fiber nonlinearities is typically approached with a generalized Gaussian noise (GGN)model.

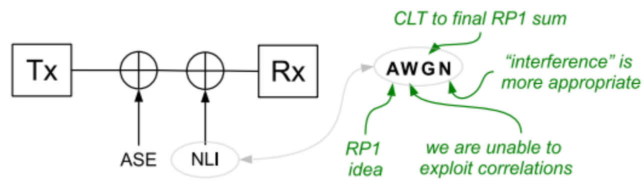

Figure 1(Gaussian noise Chanel model)

In DM optical communication systems, noise contributions arise from both ASE noise and nonlinear interference. ASE noise, primarily from EDFAs, is characterized by the EDFA's noise figure F, which is given by [1]:

$$F = \frac{\rho ASE}{G\nu h} + \frac{1}{G}$$

where **ρASE** is the ASE density, **G** is the gain, **h** is Planck's constant, and **ν** is the photon frequency. When a transparent, periodic link with **N** spans is considered, the total ASE noise power spectral density (PSD) is expressed as:

$$N_0 = N * N_{01} = N * FGh\nu B_0$$

where B0 represents the noise bandwidth. The optical signal-to-noise ratio SNR can then be calculated as:

$$SNR_{dB} = P - 10\log_{10}(N) - F - 10\log10(h\nu B_0)$$

where P is the signal power.

In DM systems, NLI due to self-phase modulation (SPM) and four-wave mixing (FWM) significantly impacts SNR, contributing noise that scales cubically with the signal power P as:

$$N_{NLI} = a_{NL} \cdot P^3$$

aNL [mW^{-2}] a normalized NLI coefficient to be found [2]. The total SNR in the DM system is given by combining ASE and NLI noise terms:

$$SNR = \frac{P}{N.N_{01} + a_{NL}\,.\,P^3}$$

This equation models the SNR in DM systems, offering insight into optimizing power and span configurations to achieve an optimal SNR with minimal nonlinear degradation.

III. SIMULINK MODEL

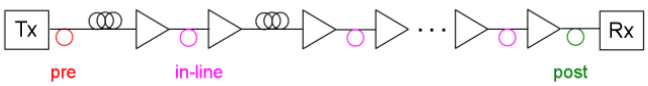

Figure 2(Dispersion Management Block Diagram)

This study uses a MATLAB simulation model to evaluate SNR in a DM optical system. A transmission (Tx) section with a 10 Gbaud symbol rate and modulation format OOK models signal generation, using a roll-off factor of 0.2 to limit spectral spreading. The DM optical link comprises spans of transmission and compensating fibers, each parameterized with realistic properties. Transmission fiber characteristics include a length of 100 km, attenuation of 0.2 dB/km, dispersion of 17 ps/nm/km, and an effective area of 80 μm². Nonlinearity is addressed with a nonlinear index n2=2.5×10^{-20} m^2/W, suitable for calculating nonlinear interference. Each span of transmission fiber is followed by a compensating fiber to achieve a residual dispersion per span (RDPS) of 0 ps/nm, using a length of 1 km and dispersion profile tailored to counterbalance transmission dispersion. A noise figure of 6 dB for optical amplifiers accounts for ASE noise. The receiver (Rx) configuration includes a Gaussian optical filter and a root-raised-cosine electrical filter, with normalized bandwidths adapted to the symbol rate. The binary detection scheme syncs with transmitted symbols via a decision-directed timing recovery method. This experiment was implemented under two conditions: **SNR vs. Power** and **SNR vs. η,** For the first condition SNR was evaluated across a range of power levels from -5 to 30 dBm to study the SNR's response at varying power inputs. And in the second condition we introduced the variable η, defined as the product of power and span count $\boldsymbol{\eta = Power \times Nspan}$, Here, power values from 0.1 to 4 mW and span values from 2 to 48 were uniformly distributed. This enabled a broader view of SNR behavior as a function of total power imparted over multiple spans.

IV. EXPERIMENTAL DEMONSTRATION & RESULT

The SNR vs. Power and SNR vs. η results illustrate the performance and limitations of our dispersion-managed optical link under different span and power configurations. Figure3 shows the variation of signal to noise ratio versus power in different number of spans.

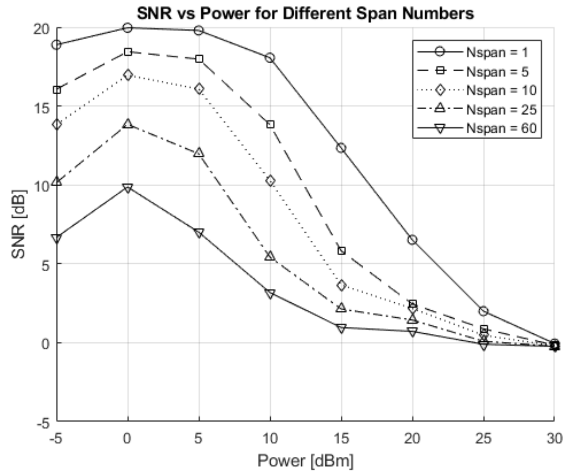

Figure 3(SNR vs Powrer in different number of spans(logarithmic scale))

The SNR initially increases with power but begins to drop as power reaches higher values across all span numbers. For lower span counts, the maximum SNR is higher and appears at lower power levels, this is because in optical systems, increasing power initially improves SNR because the signal power dominates over the ASE noise from the EDFAs. However, as power continues to increase, nonlinear effects such as self-phase modulation (SPM) and four-wave mixing (FWM) intensify, generating nonlinear noise, which reduces SNR. Nonlinear impairments scale with both power and the number of spans, leading to more significant SNR degradation in longer spans at high power levels. This trend aligns with previous research on nonlinear impairment in fiber systems, which emphasizes that optimal power is critical to minimize both ASE and nonlinear noise for multi-span link.
This result is quite like the result we obtained from SNR vs η (Power * N_{span}) in figure4. This plot shows an initial increase in SNR with η, reaching a peak, followed by a decrease as η increases further. Here, η encapsulates the combined effect of power and span count, showing that the system achieves maximum SNR at an optimal η value. This peak represents a balance point where ASE noise is minimized without significant nonlinear noise. However, as η increases, nonlinear effects dominate, causing SNR to fall, consistent with models indicating that nonlinear noise scales with power cubed (P^3). By varying η, we effectively test different nonlinear regimes, with maximum SNR at an optimal trade-off between linear and nonlinear noise effects. This behavior is consistent with findings in nonlinear fiber optics, where many research has been done to identify power and span configurations that maximize SNR by balancing ASE and nonlinear noise sources. In the experimental setup, the point where SNR reaches its maximum is critical, as it indicates the optimal balance between signal power and noise accumulation in the link. This maximum SNR value is observed at an optimal power level where the benefits of higher signal power (in terms of SNR improvement) are offset by the onset of nonlinear impairments, specifically those caused by Kerr nonlinearity and dispersion effects.

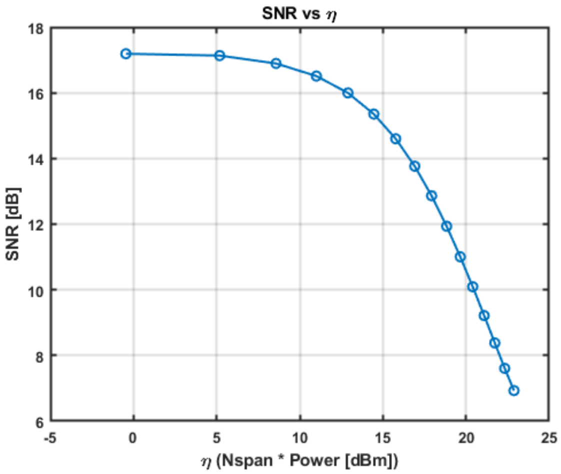

*Figure 4(SNR vs η=Power*Nspan (logarithmic scale))*

Beyond this power level, nonlinear interference begins to dominate, leading to a decrease in SNR with further power increases. This optimal power level can be considered as a threshold power, where the trade-off between signal enhancement and nonlinear distortion is optimized. Research has shown that dispersion-managed links have a unique power threshold where nonlinear effects are minimized relative to SNR gains [5]. Additionally, studies on probabilistic shaping and non-Gaussian noise suggest that achieving this optimal power requires careful balance, especially in systems affected by amplified spontaneous emission and other noise sources [6]. Thus, operating near this threshold power allows the system to maximize SNR while avoiding significant degradation due to nonlinear interference, serving as a guideline for effective power management in high-capacity fiber-optic links.

In general, the nonlinear SNR relationship, guided by the Gaussian nonlinear model (GNM), serves as a central factor in assessing system performance in terms of bit error rates or equivalent quality metrics. Figure5 shows the general relation between SNR vs Power vs N_{span} the surface plot of SNR as a function of both power and number of spans enables us to capture essential insights into system behavior [4].

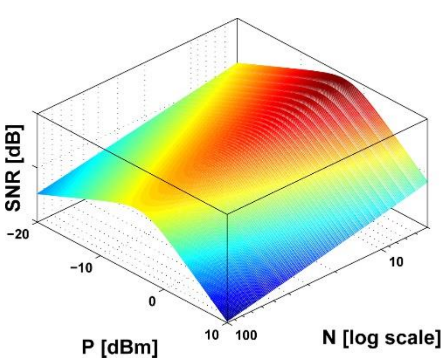

Figure 5(Qualitative example of 2-dimensional SNR surface [dB] versus both power P [dBm] and number of spans N (logarithmic scale).)

This SNR landscape represents a global view of performance, where vertical cuts illustrate how SNR varies with power at fixed span counts, revealing a bell-curve shape that peaks before nonlinear effects cause degradation. Horizontal cuts, meanwhile, showcase SNR behavior across increasing spans at a fixed power, depicting the cumulative impact of nonlinear impairments. Our aim is to leverage this framework to determine optimal conditions for minimizing nonlinear interference penalties while maximizing transmission distance. By applying these findings to our system, we gain a deeper understanding of how to set power and span parameters for best performance, reflecting broader conclusions in optical system studies regarding nonlinear tolerance and modulation efficiency.

V. Conclusion

In conclusion, this project has deepened the understanding of nonlinear impairments in dispersion-managed optical links, focusing on how SNR behaves as a function of transmission power and the number of spans. Through a systematic study, two significant insights were gained. First, an optimal power threshold was identified, where SNR reaches its maximum before nonlinear effects start to degrade the signal quality. Second, by introducing the parameter η, defined as the product of span count and power (η=Nspan×P), a more generalized approach to evaluating SNR performance across varying link configurations was established. These results underscore the challenge of managing nonlinear effects to achieve optimal link performance, which is a key concern in the field of optical communications. The data clearly shows that exceeding the optimal power threshold leads to a decline in SNR due to intensified nonlinear impairments, which is consistent with findings in previous research on nonlinear tolerance in optical systems. This optimal point serves as a useful benchmark for designing more efficient and robust optical networks, especially in long-haul communication scenarios where both high data rates and minimal signal degradation are critical. From a practical perspective, this research provides insights into configuring optical networks by balancing power and span count to maintain high SNR. Future work might explore adaptive modulation and real-time power adjustments to further enhance SNR under dynamic conditions. In summary, this project contributes a meaningful approach to managing nonlinearities in optical links, aligning with the ongoing efforts to improve performance and resilience in modern optical communication systems.

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