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Analyzing the Impact of EDFA Positioning on Signal Quality in DWDM

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DWDM Sistemlerinde EDFA Konumlandırmasının Sinyal Kalitesine Etkisinin Analizi

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Abstract

The positioning of Erbium-Doped Fiber Amplifiers (EDFAs) plays a crucial role in optimizing the performance of Dense Wavelength Division Multiplexing (DWDM) systems, particularly in addressing signal attenuation challenges in long-distance optical transmission. This study investigates the impact of EDFA placement configurations (booster, in-line, and pre-amplifier) on signal quality using OptiSystem software simulations. The research examines systems with 4 to 16 DWDM channels, operating at 10 Gbit/s per channel with 50 GHz spacing, varying total input power between -10 dBm to 5 dBm. Results demonstrate that the booster amplifier configuration performs best, while the pre-amplifier setup exhibits more pronounced degradation. The in-line amplifier configuration shows a balanced performance, effectively restoring signal strength while requiring less pump power than the booster configuration, making it a viable option for optimizing energy efficiency in DWDM systems. A critical performance threshold was identified between 10-12 channels, where all configurations experience significant changes in error performance.

Keywords *EDFA positioning, DWDM Systems, Optical Signal Quality, Q-factor, BER*

Öz

Erbiyum Katkılı Fiber Yükselteçlerin (EDFA) konumlandırılması, özellikle uzun mesafeli optik iletimde sinyal zayıflaması sorunlarının çözümünde, Yoğun Dalga Boyu Bölmeli Çoklama (DWDM) sistemlerinin performansını optimize etmede kritik bir rol oynamaktadır. Bu çalışma, OptiSystem yazılım simülasyonları kullanarak EDFA yerleşim konfigürasyonlarının (hat başı, içi ve sonu yükseltici) sinyal kalitesi üzerindeki etkisini incelemektedir. Araştırma, kanal başına 10 Gbit/s hızında ve 50 GHz aralıklı, toplam giriş gücünün -10 dBm ile 5 dBm arasında değiştiği 4 ila 16 DWDM kanallı sistemleri değerlendirmektedir. Sonuçlar, yükseltici amplifikatör konfigürasyonunun en iyi performansı sergilediğini, ön yükseltici kurulumunun ise daha belirgin bir performans düşüşü gösterdiğini ortaya koymaktadır. Hat içi yükseltici konfigürasyonu, yükseltici konfigürasyonuna göre daha az pompa gücü gerektirirken sinyal gücünü etkili bir şekilde geri kazandırarak dengeli bir performans sergilemekte ve bu da onu DWDM sistemlerinde enerji verimliliğini optimize etmek için uygun bir seçenek haline getirmektedir. Tüm konfigürasyonların hata performansında önemli değişiklikler gösterdiği 10-12 kanal arasında kritik bir performans eşiği tespit edilmiştir.

Anahtar Kelimeler *EDFA konumlandırma, DWDM sistemleri, optik sinyal kalitesi, Q-faktörü, BER*

1. Introduction

Erbium-Doped Fiber Amplifiers (EDFAs) have revolutionized optical communication networks, particularly in Dense Wavelength Division Multiplexing (DWDM) systems. These amplifiers address a critical challenge in long-distance optical transmission: signal attenuation. Their ability to simultaneously amplify multiple wavelengths suits them for DWDM systems. The positioning of EDFAs within a DWDM system significantly impacts overall performance and efficiency (Keiser 1999). Three primary configurations are commonly employed: booster amplifiers at the transmitting end, in-line amplifiers along the fiber span, and pre-amplifiers at the receiving end. Booster amplifiers increase the launch power, potentially extending reach but risking nonlinear effects. In-line amplifiers periodically restore signal strength, enabling longer transmission distances. Pre-amplifiers enhance receiver sensitivity, improving signal detection at the cost of potential noise amplification. The choice and placement of EDFAs thus become critical design considerations, directly affecting key performance metrics such as signal-to-noise ratio, bit error rate, and overall system distance (Attaouia and Malika 2017).

Numerous researchers have conducted investigations to elucidate the impact of EDFA positioning within DWDM systems. One notable study examined the effects of channel spacing and pump power on the detected signal characteristics for various EDFA placements. This research aimed to comprehensively understand how these parameters interact with EDFA positioning to

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influence overall system performance (Putrina et al. 2019). The research demonstrates that utilizing EDFAs as booster and pre-amplifiers successfully optimizes the network, meeting industry benchmarks for Power Received, Q Factor, Bit Error Rate, and Optical Signal to Noise Ratio (Asyari et al. 2018). This early study by Heens et al. introduced an innovative EDFA configuration utilizing a fiber loop mirror with a variable-ratio coupler, capable of efficiently amplifying both high and low power signals.

This design enables selective double-pass amplification for low power signals and single-pass for high power signals, effectively creating a versatile EDFA suitable for both pre-amplifier and booster applications in optical networks (Heens et al. 1998). Putrina et al. investigated the impact of EDFA positioning on signal quality in WDM transmission systems, comparing booster, in-line, and pre-amplifier configurations. Their study revealed that the in-line amplifier scenario offered the best balance between performance and energy efficiency, requiring significantly less pump power than the booster configuration while producing less amplified spontaneous emission noise than the pre-amplifier setup (Putrina et al. 2017). One of the other studies proposed a method to optimize the placement of hybrid Raman/EDFA amplifiers in mesh optical networks, aiming to minimize both 3R regenerators and hybrid amplifiers (Pedro and Costa 2018). Elkomy et al. investigated the performance of a digital optical communication link with in-line EDFA, focusing on the effects of EDFA parameters such as Erbium ion density and doped fiber length on bit error rate. Their study demonstrated that increasing Erbium ion density and doped fiber length generally improved system performance, with BER decreasing rapidly with ion density up to a certain threshold and linearly with fiber length (Elkomy et al. 2010). Researchers investigated combining EDFA and Raman amplification to tackle the quality issues in optical networks caused by physical limitations in the other literature study. They devised a clever genetic algorithm to determine the best way to upgrade existing systems (Sticca et al. 2023). In the other study, the authors conducted a parametric analysis of pre-amplifier and booster amplifier configurations employing NRZ modulation format to evaluate the BER performance under various conditions (Effendi et al. 2020).

Building upon previous research highlighting the significance of optimizing EDFA parameters and placement, this study investigates the impact of DWDM channel count on EDFA signal quality and its position within the optical link. The research methodology involves implementing up to 16-channel DWDM systems under varying input conditions to evaluate EDFA performance across various placements. The results indicate that the booster amplifier configuration demonstrates excellent performance, exhibiting good Q-factors and lower Bit Error Rates (BER) compared to other EDFA placements. These findings contribute to optimizing optical amplification strategies in high-capacity fiber optic networks.

2. Simulation Model

OptiSystem software (version 22) was employed to investigate the influence of the EDFA position on the quality of the received signal. This software was chosen for its versatility in simulating various optical link configurations within the transmission layer. A simulation model, depicted in Figure 1, was developed to analyze three distinct EDFA placement scenarios: booster amplifier, pre-amplifier, and in-line amplifier. Across all scenarios, the optical link design was maintained constant to ensure a fair comparison, with only the EDFA position varying. The model simulates a DWDM transmission system. The transmitter in each channel is modulated a 10 Gbit/s transmission speed per channel, Non-Return-to-Zero (NRZ) encoding, and Intensity Modulation On-Off Keying (IM-OOK) modulation format. The transmission frequencies span from 1543.73 nm to 1556.55 nm (192.60 THz to 194.20 THz), utilizing a 100 GHz channel spacing compliant with the ITU-T G.694.1 grid for DWDM. The number of DWDM channels varied from 4 to 16, with the total input power maintained at 0 dBm, ensuring equal power distribution across each channel.

The outputs of the eight transmitters are multiplexed into a single optical signal, which the EDFA then amplifies. The EDFA was configured for forward pumping at 980 nm with a pump power of 100 mW, and this configuration was consistently applied across all three EDFA placement scenarios: booster, in-line, and pre-amplifier and it utilizes the default EDF model provided within OptiSystem. At the receiver end, the signal is demultiplexed into individual channels. Each receiver channel includes an Avalanche Photodiode (APD), a low-pass Bessel filter, and a regenerator. The performance of the EDFA in each configuration is evaluated by analyzing the Bit Error Rate (BER) and the Q-factor using the eye diagram analyzer at the output of each receiver. The BER is calculated by comparing the number of erroneous bits to the total number of transmitted bits. At the same time, the Q-factor is derived from the eye diagram by measuring the separation between the signal levels for logical '1' and '0' and their respective noise levels.

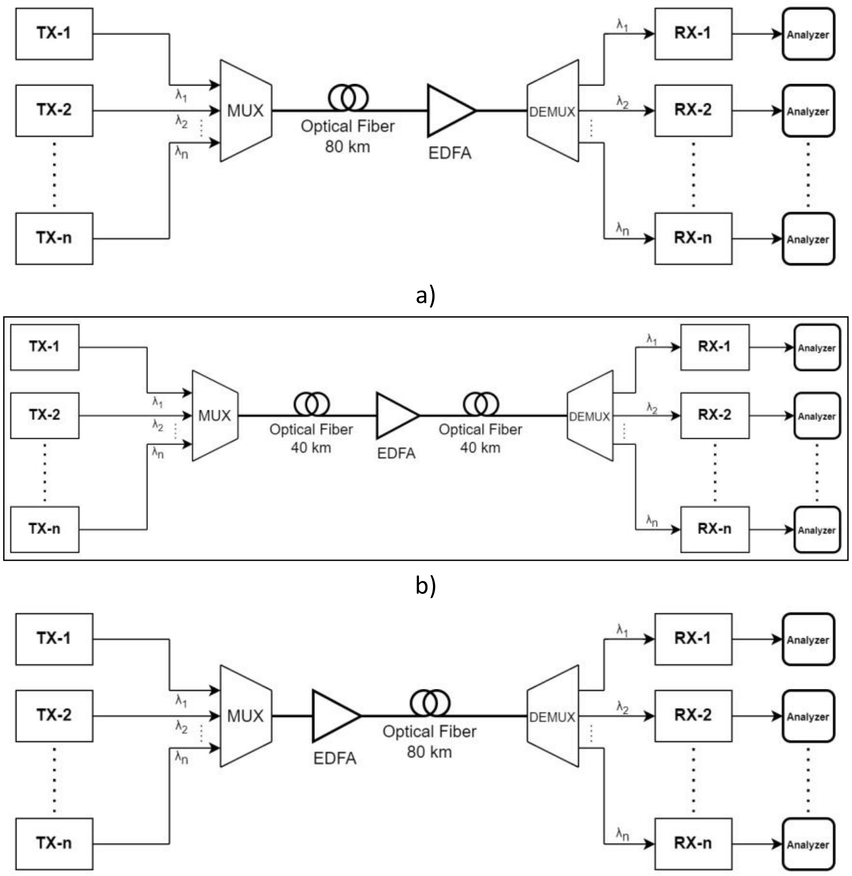

Figure 1. DWDM links with EDFA configurations in booster, in-line, and pre-amplifier setups as Figures 1a, 1b, and 1c, respectively.

3. Results and Discussions

The simulation results depicted in Figure 2 illustrate the relationship between the maximum Q-factor and the number of channels for three distinct amplifier configurations in a WDM system. The investigation with a fixed total input power of 0 dBm demonstrates that the booster amplifier configuration exhibits superior performance across all channel counts, maintaining Q-factors between 5.54 and 4.82. The in-line amplifier shows intermediate performance characteristics, with Q-factors ranging from 5.20 to 4.78, while the pre-amplifier configuration demonstrates the most pronounced degradation, with Q-factors declining from 5.12 to 4.38. A notable observation is the steeper degradation in performance between 4 and 8 channels across all configurations, followed by a more gradual decline beyond eight channels. This behavior suggests that inter-channel effects and ASE noise accumulation at higher channel counts predominantly limit the system's performance. The convergence of Q-factors for the booster and in-line configurations at 16 channels ($\Delta Q \approx 0.04$) indicates that the advantages of the booster configuration become less pronounced in highly multiplexed systems.

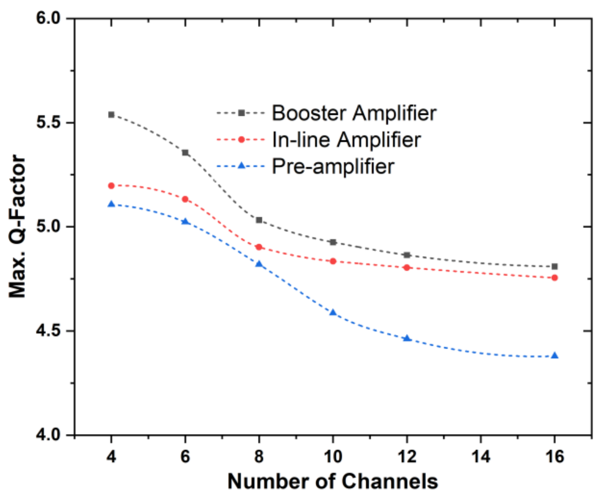

Figure 2. Comparative analysis of maximum Q-factor performance for proposed EDFAs as a function of channel number

The results demonstrate the BER performance characteristics across multiple amplifier configurations in Figure 3, with measurements conducted at a fixed total input power of 0 dBm. The Booster Amplifier configuration exhibits superior performance metrics, achieving a minimum BER of 1×10^{-7} at 4-channel operation, attributed to its optimal positioning for ASE noise management and enhanced OSNR characteristics. A critical threshold manifests between 10-12 channels, where all configurations experience an inflection point in their error performance, likely due to the onset of interchannel crosstalk and nonlinear effects such as Four Wave Mixing (FWM) and Cross-Phase Modulation (XPM). The pre-amplifier configuration shows increased susceptibility to performance degradation, with BER deteriorating to approximately 1×10^{-4} at 16 channels, suggesting compromised noise figure characteristics at reduced per-channel power levels. Implementing chromatic dispersion compensation modules would mitigate the system's BER degradation while enhancing the transmission performance metrics across all amplifier configurations.

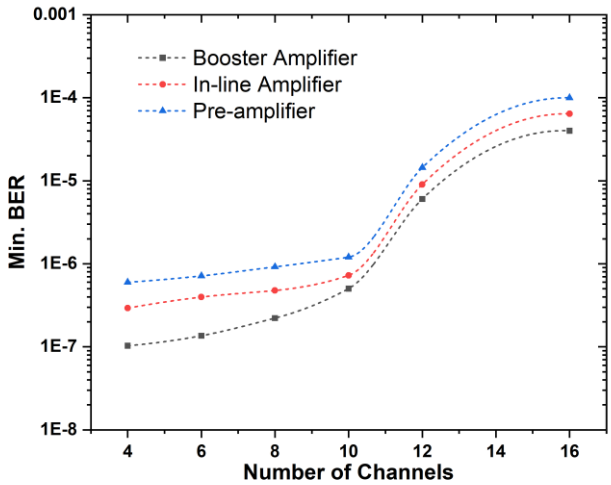

Figure 3. Minimum Bit Error Rate (BER) as a function of the number of channels for three types of EDFA

The spectral analysis of Q-factor performance (Figure 4) across the C-band frequency range (1543.73 nm to 1556.55 nm) reveals distinct behavioral patterns for different amplifier configurations in the 16-channel WDM system. The booster amplifier demonstrates exceptional performance stability, maintaining a Q-factor of approximately 4.8±0.1 across the entire frequency range, with minimal spectral variations. The in-line amplifier exhibits comparable stability with slightly lower Q-factor values, averaging around 4.7±0.1, and shows a good correlation with the booster amplifier's performance trend, particularly in the higher frequency region (>193.6 THz). In contrast, the pre-amplifier configuration displays more pronounced frequency-dependent variations, with Q-factor fluctuations between 4.2 and 4.5. It demonstrates increased susceptibility to performance degradation, particularly in the lower frequency region. This frequency-dependent behavior can be attributed to the combined effects of gain tilt characteristics and ASE noise accumulation, which become more pronounced in the pre-amplifier configuration due to its position in the transmission link.

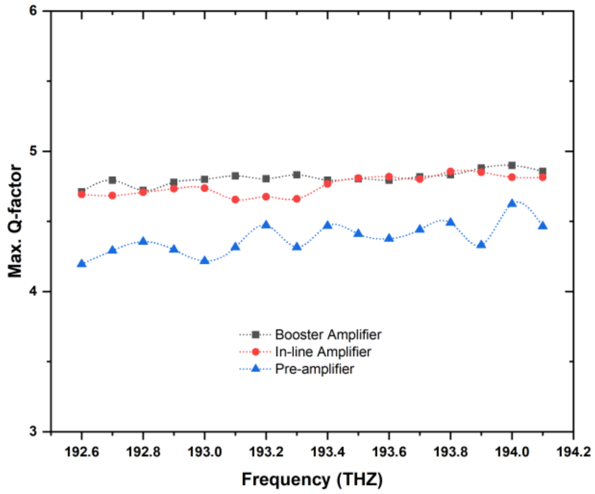

Figure 4. Frequency-Dependent Maximum Q-Factor Analysis for three different EDFA positions while the input signal has 16-channels with 0 dBm total input power.

Investigating a 16-channel WDM system employing an in-line amplifier configuration reveals a distinct correlation between total input power and system performance metrics in Figure 5. The system exhibits two competing phenomena as the aggregate input power varies from -10 dBm to 5 dBm (corresponding to per-channel powers from -22 dBm to -6 dBm). The Q-factor demonstrates a monotonic improvement from 4.85 to 5.0 in the lower power regime (-10 dBm to 0 dBm), followed by saturation characteristics above 0 dBm, suggesting the onset of nonlinear effects such as Self-Phase Modulation (SPM) and XPM. Conversely, the BER measurements show an inverse correlation, deteriorating from approximately 3×10^{-7} to 8×10^{-7} as input power increases. This behavior indicates that higher input powers enhance the system's OSNR, improving Q-factors, worsening nonlinear impairments, and increasing BER. The optimal operating point is around -4 dBm total input power, where a favorable compromise between OSNR enhancement and nonlinear penalties is achieved.

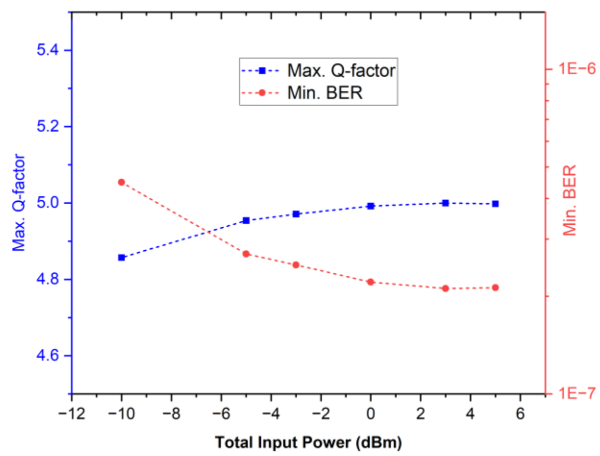

Figure 5. Maximum Q-factor and minimum BER versus total input power for a 16-channel WDM system with In-line amplification.

4. Conclusions

This study highlights the crucial role of EDFA positioning in enhancing signal quality within DWDM systems, particularly under varying channel counts and input power levels. The findings indicate that the booster amplifier configuration consistently outperforms others, achieving higher Q-factors (5.54-4.82) and lower BER values (as low as 1×10^{-7} at four channels). The in-line amplifier offers a balanced approach, while the pre-amplifier is more prone to performance degradation, especially at higher channel counts. A critical performance threshold was observed between 10-12 channels. The optimal operating point for the in-line configuration is around -4 dBm total input power, effectively balancing OSNR enhancement and nonlinear effects. Future work should aim to apply these insights in real-world scenarios, such as metropolitan area networks.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author 1: Characterization, methodology and report.
Author 2: Research, characterization, methodology and report.

Declaration of Competing Interest
The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability
All data generated or analyzed during this study are included in this published article.

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