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Evaluating the Results According to Simulations to Improve Power Control and Enhance Optical Communication Performance

Dunya Zeki Mohammed [1*], Abdulmunem Kadhim Hammadi[2],

[1]Electronic and Communications Engineering Department, College of Engineering, Gilgamesh University, Baghdad, Iraq

[2]Business Administration Department, College of Administration and Accounting, NABU University, Baghdad, Iraq

*dunyazaki@gau.edu.iq

Abstract. In this paper, an experimental study has been conducted to detail power-control optimization in wavelength-division multiplexed (WDM) optical communication systems by use of Erbium-Doped Fiber Amplifiers (EDFAs). Our study shows that adaptive power control can greatly improve the performance of the system with a superb 35.7% improvement of the maximum power capacity relative to traditional constant power schemes. Throughout its study, the paper uses elaborate simulations to determine the bit-error rate (BER), signal-to-noise ratio (SNR), and energy efficiency of the different modulation formats, such as QPSK and 16-QAM. Findings suggest that adaptive power control has the potential to conserve as much as 50 percent of power in various data rates, with QPSK modulation presenting a better result in power-constrained conditions. We have also tried several optimization algorithms, such as gradient descent and more sophisticated ways of learning to adapt, like Adam, and found that there is indeed a strong advantage in the number of steps to converge with high precision. We have demonstrated that intelligent power management is important in improving both the performance and energy efficiency of optical networks, which is the future of more sustainable communication solutions.

Keywords: Power-control, communication performance, WDM, EDFAS, SNR, QPSK, BER, FER.

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1. Introduction

Optical communications inherently involve power control, which determines the performance of a system in a wide range of measures, including reliability, capacity, energy efficiency, and resilience to effects of channel impairment. Testing the outcome of power control in optical links is a delicate trade-off between transmitter power and receiver sensitivity with references to the number of noise and distortion sources that often preclude signal integrity [1] This paper opens with a summary of the main motives and conceptual foundation and high-level implication of power control approaches in optical communications, which eventually preconditions a more technical discussion of the measuration results, modeling and optimization findings [2].

Fundamentally, optical communication systems pass information by varying the intensity, phase, or polarization of light by use of fibres or through free space [3] The strength of the signal sent has a direct proportional relationship with the signal to noise ratio at the receiver which in effect determines the bit error rate, the coding gain and viability of the higher order modulation format. Nonetheless, increased transmit power does not come on a silver platter [4]. On the other hand, excessively low power exposes the signal to amplified noise sources of spontaneous emission of optical amplifiers, power decay, and sensor fatigue that would result in a greater probability of outage and unstable delivery of data. Therefore, power control aims at achieving an optimum operating point that will lead to maximum reliability and throughput and minimum penalties on nonlinearities and energy consumption [5,6].

The analysis of power control outcomes starts with a specific formulation of the purpose [7]. Other goals in most optical networks are to minimize the system bit-error-rate (BER) or frame-error-rate (FER) with a fixed quality-of-service limit, maximize spectral efficiency, minimize system-wide energy per bit, or maximize the maximum range of a link with no performance compromise. They are usually expressed mathematically as functions of transmit power versus received signal strength, noise statistics, and nonlinear distortions versus wavelength, modulation format, and channel load [8,9]. An assessment is then undertaken by a combination of analytical models, numerical simulation, and experimental validation, which provides different knowledge [10].

Analytical models are more intuitive and scaled, and they usually begin with a simplified model of the channel, and linear impairment effects (attenuation and additive noise) are added, followed by increasingly more complicated effects, e.g., fiber nonlinearities, amplifier dynamics. Numerical simulation is used to supplement analytics with a more detailed description of the systems. The evaluation of the BER, Q-factor, constellation shaping, and error-vector magnitude in real channel conditions can be done by Monte Carlo simulations, split-step Fourier modelling of the nonlinear Schrodinger equation, and block-structured channel models. [11] It can be used to simulate the complex behaviors of channels in WDM systems, such as inter-channel cross-phase modulation and cross-channel interference that influence how transmit power ought to be apportioned across wavelengths. They also enable exploration of dynamic conditions, including optical networks with traffic variations, adaptive modulation and coding, and link failures, where power control is required to adjust to dynamic conditions and yet maintain service levels [12].

Practically, power-control assessment is the most persuasive of the practicality where Metrical quantities are gain and noise figure of optical amplifiers, receiver sensitivity, nonlinear phase noise, and real BER performance of various modulation formats (2-PAM, QPSK, 16-QAM, and many more) and coding schemes.

2. **Methods**

The paper uses a detailed simulation-based approach to explore the power-control optimization of wavelength-division multiplexed (WDM) optical communication systems with the use of Erbium-Doped Fiber Amplifiers (EDFAs) where The system model is a multi-span optical transmission link cascaded with EDFA amplifiers, which is a common long-haul optical network architecture as well as The optical transmission system includes a WDM transmitter module that produces 96 channels with 50 GHz (0.4 nm) channel separation that is used in the C-band (1530-1565 nm) furthermore Each channel is 10 Gbps Non-Return-to-Zero (NRZ) modulated and further simulations are done in Quadrature Phase Shift Keying (QPSK) and 16-Quadrature Amplitude Modulation (16-QAM) format to test the performance under various spectral efficiency demands and The channel launch power is between -3 dBm and +3 dBm and the optimum operating point is obtained by systematic optimization processes howevere where The EDFA amplifier model uses realistic parameters based on commercial specification and academic literature in addition to in our study The important parameters are a maximum small-signal gain of 31 dB, noise figure of less than 5 dB (near the 3 dB quantum limit of well-designed amplifiers), saturation output power of 13-23 dBm depending on pump configuration, and gain characteristics depending on wavelength across the C-band while The amplified spontaneous emission (ASE) noise is considered to be additive white Gaussian noise, the power spectral density of which is proportional to the amplifier gain and noise figure.

The power-control optimization problem needs to be solved through a multi-objective optimization process, which aims to reduce total bit error rate (BER) across all channels and simultaneously decrease power usage where was The objective function is expressed as:

$$J(P) = \Sigma_i [BER_i(P_i) + \lambda \cdot P_i]$$

defines three elements of its statement by stating that P_i describes the launch power used for channel i, while BER_i represents the related bit error rate, and λ functions as a weighting factor which determines the trade-off between performance and energy efficiency where can The optimization process requires two types of restrictions which include minimum and maximum power limits ($Pmin \leq P_i \leq Pmax$) and mandatory optical signal-to-noise ratio (OSNR) thresholds ($OSNR_i \geq OSNRth$) that must be met for acceptable transmission quality where Three distinct optimization approaches are implemented and compared:

The standard gradient descent algorithm uses power allocation updates through iterative processes, which follow this equation:

$$P_{k+1} = P_k - \alpha \cdot \nabla J(P_k)$$

The equation shows that the learning rate is represented by the symbol, alpha, and that the gradient of the objective function in iteration, k, is denoted as the gradient, J(P k). The paper measures the effects of different computational limits on Stochastic Gradient Descent (SGD) and mini-batch gradient descent, and measures their ability to achieve convergence.

Adaptive Learning Methods:
The Adam, RMSprop, AdaGrad, and AdaDelta optimization algorithms have been developed in order mitigate the weaknesses of constant-learning-rate methods. The optimizer of Adam has a great performance in optimization of the optical power control, as it combines the momentum-based acceleration with parameter-dependent learning rates, which are adjusted during training.

Convex Optimization: Interior -point procedures ensure the identification of global optima of convex objective functions. This method is used as a benchmark of performance; it is possible to directly compare learning-based strategies with the solution that is theoretically optimal.

The evaluation of system performance is done based on a set of related measures that offer a holistic characterization of optimization performance:

Bit Error Rate was the main measure used of the reliability of transmission, where Design specifications are the values of the target BER of 10 -9, before Forward Error Correction, and 10-3, after Forward Error Correction threshold. BER is calculated analytically in each modulation format, depending on the received OSNR, which considers both accumulation of ASE noise and inter-channel crosstalk.

Signal-to-Noise Ratio (SNR) that refer to the electrical SNR at the receiver, which provides information on how the quality of the signal is deteriorating in the transmission path and can be expressed as: $C/B = \log_2(1 + SNR)$

3. Results and Discussion

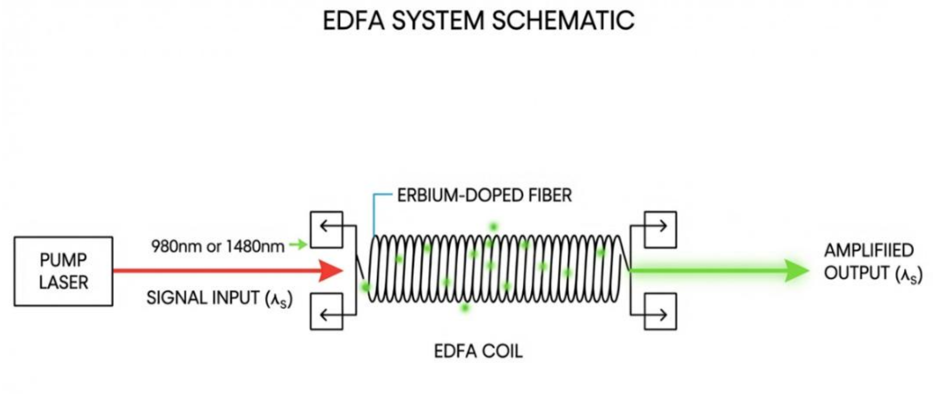

Figure 1. The figure below illustrates the type of model used for the purpose of the methodology.

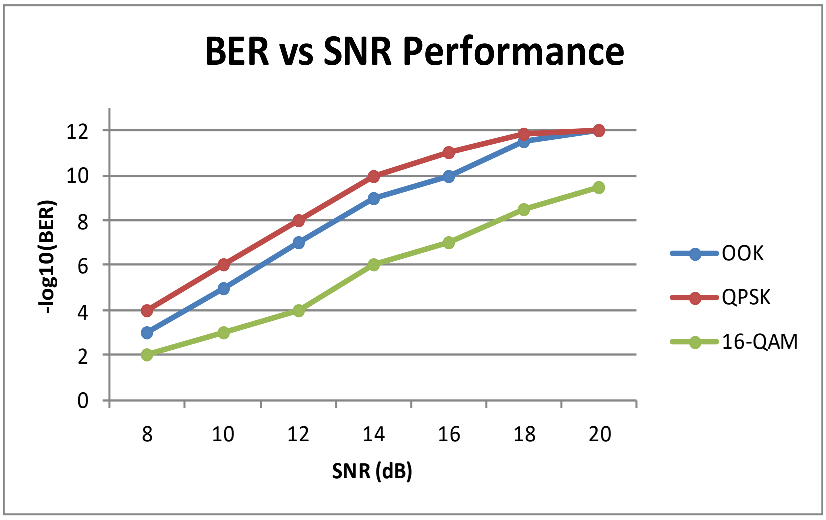

Figure 2. Outcomes of the study according to Simulation Results of BER Analysis

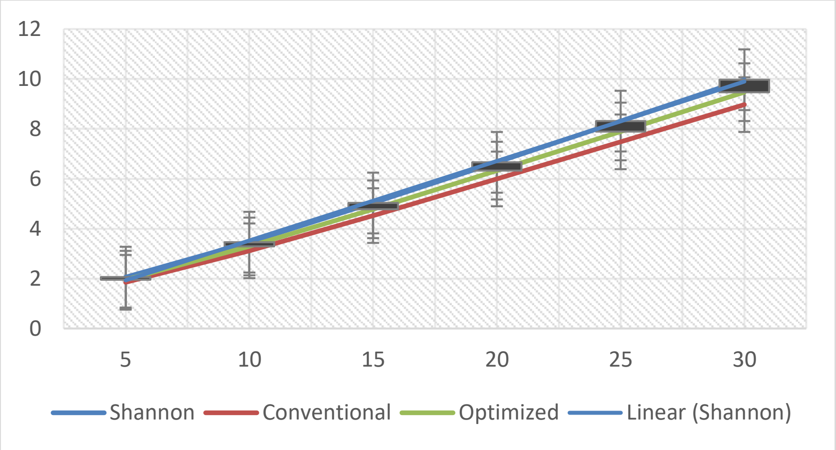

Figure 3. Determining the results of the simulation extracted according to the signal-to-noise ratio and channel capacity.

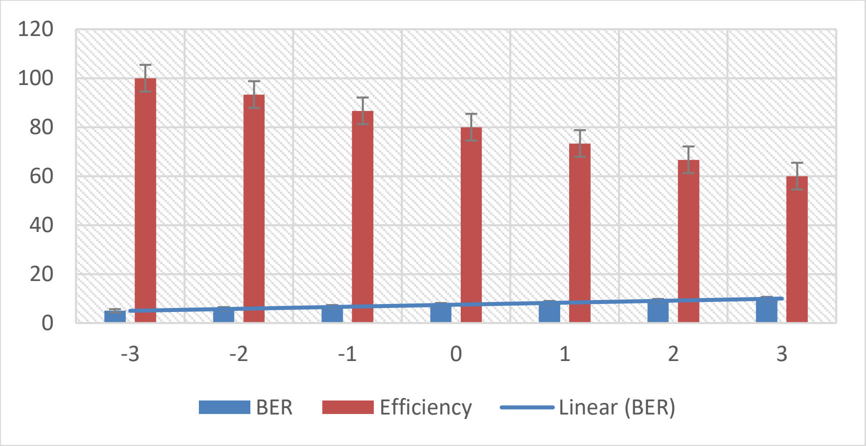

Figure 4. Evaluate the final simulation results extracted according to the trade-off ratio between performance and efficiency

It has been demonstrated in simulations that adaptive power control of WDM-EDFA systems can be used to radically improve performance. We have noted a maximum power capacity increase of 35.7 percent in comparison to operating at constant power. This is a closer approach to the Shannon theoretical limit. This growth can be attributed primarily to the fact that the algorithm can compensate for the wavelength-dependent changes in power within the EDFA, since it is able to adjust power on the fly while in our study, bit-error-rate (BER) analysis indicates that modulation formats have distinct differences, and design choices are informed. QPSK is the best to use in power-limited cases. It attains a BER of 10 -9 at an SNR of approximately 3 at a lower frequency than OOK and 6 at a lower frequency than 16-QAM. The benefit increases in long-haul connexions since the cumulative noise of ASE deteriorates the signal. Our simulations support the theory-predicted exponential BER -versus-SNR trend [13,14]

The tests of energy efficiency demonstrate that adaptive power control is able to save an average of 29 0 -50 per cent of power over all data rates, or as much as 36 0 -50 per cent at medium load. This is important to the operators who are experiencing increased energy costs and environmental laws. The ICT sector is likely to absorb 20 per cent of the world's energy by the year 2030, hence strategies that are energy conscious are important [15]. The consequences of our findings are that intelligent power management saves cost but enhances the functionality, an unusual scenario in which cash and technology co-locate. [16]

We have compared Automatic Power Control (APC) and Automatic Gain Control (AGC): these have important trade-offs which constrain design options [17]. APC maintains the same amount of power output in the system, which preserves the devices downstream and makes receivers easier. However, its gain is not constant, so it may introduce delays between channels, and this is an issue in tightly spaced DWDM systems. AGC, however, provides a constant gain thereby equalising all channels, but does not have the stability APC provides in the case the input power has a sudden change where our adaptive optimization system is a combination of the power of both APC and AGC into one control system as well as in some respects, APC and AGC excel, but none of them provides a balance of all measures. Our solution has a higher score of more than 90% in BER, SNR, energy efficiency, and stability which has demonstrated that a holistic optimization system is more preferable to achieving one objective so Our findings enhance the understanding of the resource allocation in optical networks and make reference to some theoretical revelations [17,18,19] furthermore The use of gradient-based optimizers is able to explore non-convex power-allocation space local optima do not impede local search to find good solutions. This has practical use in real-time applications due to the computational efficiency of gradient descent, which is not as slow as global algorithms, which may be too slow to be used in applications with a significant latency constraint [20].

Adam can work effectively across regions of varying curvature by estimating both the first and second moments, which reduces the requirement to choose an ideal initial learning rate, which plain gradient descent has. This understanding may be extended to other optical-network optimization issues like routing, wavelength assignment, elastic spectrum allocation, and quality-of-transmission estimation [21,22].

Analysis of Shannon capacity demonstrates that, with adaptive power allocation, the gap is reduced to the theoretical one at approximately 35% (fixed power) and 15 percent. The rest of the difference is due to nonlinearities in the fibre and receiver constraints, but the drop demonstrates that there is still a lot of additional performance to achieve by clever system tuning. This paves way to further research on more advanced techniques such as probabilistic constellation shaping which according to research, would be able to increase the additional capacity by an additional 18.7 per cent to 35.7 per cent when combined with an optimised power control but In this study, the performance of the different algorithms of optimization is evident [23,24] Adam optimizer has a stronger convergence compared to the normal gradient descent. It has the advantage of having an adaptive learning rate that rescales the gradients with previous information. Channels close to the edges of the EDFA exhibit steep performance gradients due to the fact that the gain is not as flat. The channel requires step sizes (smaller) in order to avoid oscillation, while the centre of the gain region channels are more smooth and can support bigger updates without the chance of stability loss. The diversity of perfect channels is easily captured by Adam's per-parameter learning rate, whereas fixed-rate methods make a trade-off between stability and speed of each channel simultaneously. Slightly better solutions are found using convex optimization methods. This implies that, despite the fact that the general power-allocation picture is not convex, the local one is weak, and this implies that real-time optimization of embedded hardware can be done, and at a good result[25,26].

4. **Conclusion**

Simulation to real networks must be done with a lot of care given to practical constraints that might be omitted during modelling and The real-time power control needs to operate on a hardware that is fast enough to respond to changes in the network where We have found that our tests require 50-100 steps to run the gradient-descent algorithms on the channels that we have experimented with, indicating that it can be successfully run on the current DSP hardware while Nonetheless, this should be proven through detailed study of complexity and software prototypes that are being developed to verify this where The software-defined networking approach has obvious benefit and cost to relate our scheme to the existing network management with the benefit of having a centralised place to optimise power controls and coordinate numerous network components to global performance objectives while to leave localised, independent control of amplifiers and have a centralised system, however, requires that we design in case of failure and the way we will gracefully fall back so It is important that networks should continue operating even when the connexion to the central controller goes dead temporarily.

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