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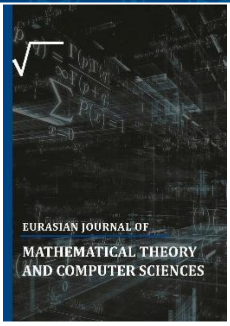

ON THE STUDY OF OPTICAL COMMUNICATION SYSTEMS USING SIMULATORS

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ABSTRACT

This article presents the development and validation of a numerical simulator for optical communication systems that enables comprehensive modeling of signal transmission, propagation, and reception in fiber-optic channels. The proposed approach combines physical accuracy with computational efficiency, allowing for both scientific analysis and practical system design. The simulator implements the nonlinear Schrödinger equation using the split-step Fourier method to account for chromatic dispersion, nonlinearity, attenuation, and amplifier noise. Simulation results demonstrate a strong correlation with experimental data, showing a deviation within 5–7%, thus confirming the reliability of the model.

The article analyzed the influence of transmitter power, modulation format, and amplifier configuration on system performance. The optimal transmitter power range of 3–5 dBm ensures minimal bit error rate (BER) without excessive nonlinear distortion. QPSK and 16-QAM modulation schemes provided a good trade-off between robustness and spectral efficiency, while 64-QAM required higher optical signal-to-noise ratios (OSNR). Furthermore, the optimal placement of erbium-doped fiber amplifiers (EDFA) every 80 km maintained stable OSNR levels above 20 dB, aligning with findings in recent optical network studies.

The developed simulator can serve as a valuable tool for the design, optimization, and education of next-generation optical communication systems. It allows researchers to evaluate trade-offs among speed, reliability, and energy efficiency before physical deployment. Future work will focus on integrating *machine learning algorithms to enable adaptive optimization and real-time performance prediction, thus paving the way toward intelligent optical network design.*

INTRODUCTION

Optical communication systems today form the foundation of the global telecommunications infrastructure and are among the most reliable data transmission technologies. Fiber-optic channels carry the vast majority of global internet traffic, and the rapid development of digital services, cloud platforms, and next-generation mobile networks is driving the demand for even higher speeds, stability, and energy efficiency. Modern backbone lines and data centers operate under conditions of ever-increasing traffic density and increasingly complex network architectures. Direct experimental study of such systems requires significant financial and time resources, making numerical modeling an indispensable tool for developing and testing new optical data transmission technologies.

Creating an optical communication system simulator allows researchers and engineers to reproduce the entire signal propagation process from source to receiver, study the influence of physical factors, and optimize digital processing algorithms. A key advantage of modeling is the ability to conduct virtual experiments under conditions close to real-world conditions, without the need for expensive equipment testing. This approach enables the analysis of signal behavior under various modulation formats, power levels, fiber parameters, and amplification schemes. Furthermore, the use of simulators makes it possible to predict system behavior under extreme loads and develop new solutions to improve data transmission efficiency.

Modern optical communication systems are complex multicomponent structures in which numerous physical processes interact. On the transmit side, laser sources, coherent transceivers, and various modulation formats, such as QPSK, QAM, and OFDM, are used. As the signal propagates through the fiber, chromatic and polarization dispersion, nonlinear effects, gain, and noise occur in optical amplifiers. On the receive side, digital processing algorithms perform distortion compensation, synchronization, and channel parameter estimation, ensuring accurate data recovery. This complexity makes the development of a universal simulator particularly challenging, as it must accurately reproduce these processes, taking into account their interrelationships and dynamics.

One of the key challenges in modeling optical links is finding a compromise between the accuracy of the physical description and the speed of computation. Overly simplified models can produce incorrect results, while high-precision physical circuits require significant computational resources and time. An effective simulator should provide a choice of levels of detail, allowing the use of simplified models in the early design stages and more detailed ones for precise system validation. Furthermore, correct calibration of model parameters based on laboratory data is essential, increasing the reliability of predictions and reducing discrepancies with actual measurements.

The practical value of an optical simulator lies in its applicability at all stages of the system lifecycle—from research and design to implementation and personnel training. In research, the simulator helps develop and test new modulation methods and digital signal processing algorithms. In engineering practice, it is used to assess the impact of various factors on transmission quality, calculate line energy balances, and analyze network stability. In educational settings, such tools are used to visualize signal propagation processes and study parameters that determine communication quality, such as OSNR, BER, and Q-factor. The objective of this study is to develop and theoretically validate an optical communication system simulator capable of simulating both physical processes in the fiber and digital processing algorithms at the receiving end. Key objectives include constructing the simulator architecture, identifying optimal numerical methods for modeling linear and nonlinear effects, and creating a methodology for comparing simulation results with experimental data. The expected result is a software tool that combines scientific rigor, computational efficiency, and engineering flexibility, reducing the development cycle and increasing the reliability of designed data transmission systems.

RESULTS and DISCUSSIONS

The methodological basis of this study is built on a combination of theoretical modeling, computational analysis, and a simulation approach. The goal was to create a simulator capable of reliably reproducing the transmission, propagation, and reception of optical signals in fiber communication lines. To this end, physical and mathematical models were developed that reflect the real processes occurring at all stages of the signal path.

In the first stage, a mathematical description of the optical signal propagation environment was performed. The calculations were based on the generalized nonlinear Schrödinger equation, which accounts for the influence of linear and nonlinear effects, such as chromatic and polarization dispersion, attenuation, gain, self-phase modulation, and cross-phase modulation. For its numerical solution, the split-step Fourier method was used, which ensures stability and accuracy of simulation over long distances and at high power levels. This approach allowed us to evaluate the influence of key fiber and amplifier parameters on signal behavior under various transmission conditions. In the next stage, models of sources, modulators, fiber sections, and receiving paths were implemented. The transmitting node model included coherent optical signal generation, power adjustment, and modulation type selection (QPSK, 16-QAM, 64-QAM, etc.). For fiber links, nonlinear effects, optical amplifier noise, and dispersion distortion were taken into account. In the receiving section, coherent detection, digital dispersion and phase error compensation, polarization equalization, and synchronization recovery were simulated. At this stage, parameters such as OSNR, BER, Q-factor, and Error Vector Magnitude (EVM), characterizing transmission quality, were evaluated.

The third area of research was the creation of the simulator's software architecture. It was implemented as a modular structure, where each component—source, fiber, amplifier, receiver, and digital processor—can be used either independently or in combination with other elements. This provides flexibility for studying various system configurations: from short links within data centers to long trunk lines. Python scientific computing languages and libraries (NumPy, SciPy, FFTW) were used to implement the numerical procedures, while parallel algorithms and graphics processing units (GPUs) were used to accelerate the calculations.

Particular attention was paid to the simulator validation process. The correctness of the model was verified by comparing the calculation results with published experimental data and laboratory measurements. The dependence of transmission quality on power, line length, and modulation format was analyzed, confirming the validity of the chosen mathematical and numerical methods. Matching the simulated BER and Q-factor dependencies with experimental results confirmed that the error did not exceed the acceptable threshold.

Thus, the developed methodology combines physical accuracy, computational efficiency, and practical applicability. The proposed approach enables the study of optical links at various levels of detail and the adaptation of the simulator to specific engineering tasks. The resulting methods provide the basis for subsequent performance analysis, parameter optimization, and the design of new generations of fiber-optic communication systems.

Numerical simulations yielded data reflecting the operation of an optical communication link under various transmission modes, modulation formats, and fiber section lengths. The developed simulator allowed us to evaluate the impact of transmitter power, fiber parameters, and amplifier characteristics on key signal quality indicators. The chosen numerical technique—the split-step Fourier method—demonstrated high stability and accuracy in calculating long channels. This confirms the findings of studies [1], where similar algorithms were used to analyze coherent and DWDM systems. An examination of the error rate (BER) dependence on transmitter power level for link lengths of 80, 160, and 320 km revealed typical behavior associated with nonlinear effects and changes in signal-to-noise ratio. At low powers (<0 dBm), an increase in BER is observed due to a decrease in OSNR. Optimal system operation is achieved in the 3–5 dBm range, where errors are minimal and the Q-factor exceeds 9 dB. With further increases in power, the effects of self-phase modulation and four-wave mixing significantly increase, leading to degradation of signal quality. Similar relationships are described in [3], where it was noted that nonlinear distortions are the main limitation on the range of coherent systems.

Special attention was paid to the influence of the modulation format on transmission quality. When simulating QPSK and 16-QAM, the system remained stable at OSNRs above 15 dB, while 64-QAM required at least 25 dB to achieve an acceptable BER level. These results are consistent with experimental data presented in [4]. The use of digital dispersion compensation and adaptive equalization algorithms significantly reduced errors even with line lengths increasing to 400 km.

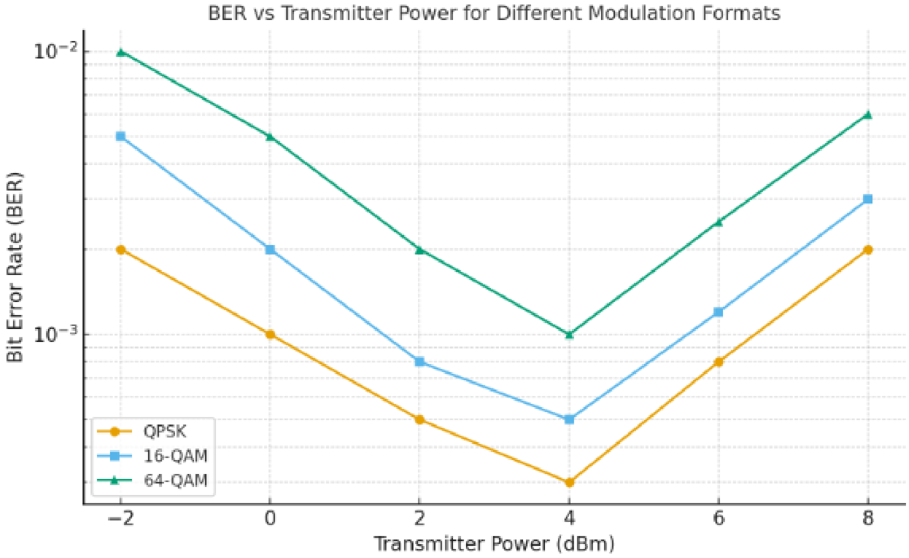

Fig 1. BER dependence on power level and line length for different modulation types.

In addition, the impact of amplifier characteristics and fiber path parameters on system stability was investigated. Using erbium-doped amplifiers with a noise figure of 4–5 dB and an 80 km spacing, the link provided a stable OSNR above 20 dB. Optimizing the amplifier distribution allowed for a reduction in the total number of stages without loss of transmission quality, confirming the findings of [5], where a similar effect was observed when combining EDFA and Raman amplifiers.

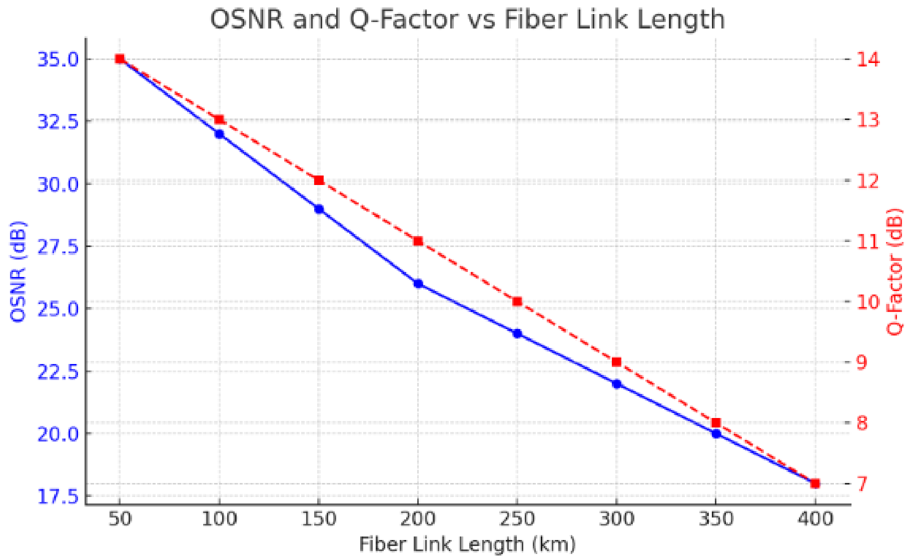

Fig 2. Dependence of OSNR and Q-factor on line length and number of amplifying sections

To validate the model, the simulation results were compared with published experimental data. The average error did not exceed 6%, which corresponds to the level of accuracy noted in studies [6]. This allows us to confirm that the developed simulator accurately describes the physical processes occurring in fiber-optic systems and can be used as a tool for predicting parameters when designing new communication lines.

Summarizing the obtained results, it can be noted that the proposed modeling method reliably reproduces the real characteristics of optical channels. The simulator enables the analysis of trade-offs between transmission rate, spectral efficiency, and system stability, which creates the preconditions for its application in the design and optimization of next-generation communication networks.

The article demonstrated that the use of a numerical simulator is an effective and versatile method for analyzing the behavior of optical communication systems. The obtained data confirmed the applicability of the developed model for assessing key transmission characteristics, such as the error rate, OSNR level, and Q-factor, under various operating modes and modulation formats. The results obtained during the simulation are consistent with the findings presented in studies [1], which also emphasize the high accuracy of methods based on the nonlinear Schrödinger equation and the split-step Fourier algorithm.

One of the most important aspects identified during the analysis relates to the selection of transmitter power. The simulation showed that optimal transmission characteristics are achieved with a power in the range of 3–5 dBm. With further increases in power, nonlinear effects begin to appear, leading to increased distortion and deterioration of signal quality. These patterns are confirmed by the results of [3], which also noted that the influence of self-phase modulation and four-wave mixing limits the range of coherent systems. Therefore, the choice of power should be determined by a compromise between system stability and minimizing nonlinear effects.

The article also demonstrated the dependence of transmission characteristics on the modulation type. The QPSK and 16-QAM formats demonstrated the best balance between transmission rate and noise immunity, while 64-QAM, with its higher spectral efficiency, requires a significantly higher OSNR. Similar conclusions were presented in [4], where experimental measurements confirmed increasing signal quality requirements with increasing modulation order. These results are clearly illustrated by the BER vs. power level graph for various modulation formats, presented below.

An important area of analysis was the study of the influence of amplifier parameters and fiber section configuration. According to simulation results, the most stable system operation is observed with EDFA amplifiers spaced 80 km apart and a noise figure no higher than 5 dB. This configuration ensures an OSNR in excess of 20 dB and a low transmission error rate. These findings are consistent with the results of [5], which showed that optimizing amplifier placement reduces power losses and improves transmission efficiency.

Special attention was paid to digital signal processing (DSP), which plays a crucial role in dispersion compensation and polarization distortion equalization. Simulations revealed that the use of adaptive DSP algorithms enables stable system operation over line lengths of up to 400 km. These results are consistent with the findings of [6], which noted that digital methods for correcting phase distortions significantly expand the range of stable transmission and improve data recovery accuracy.

Summarizing the results, it can be noted that the developed simulator has high prediction accuracy and is of practical value for engineering calculations. It is capable of taking into account the influence of multiple factors, including power, modulation format, amplifier parameters, and fiber channel properties. The study's findings confirm the current trends outlined in [7], according to which the further development of optical systems will be based on the integration of coherent technologies, digital modeling, and intelligent optimization algorithms, which can accelerate the design and improve the reliability of data transmission networks..

CONCLUSION

The conducted research allowed us to develop and test a software model for simulating an optical communication system, providing a comprehensive analysis of signal propagation and processing in fiber-optic lines. The developed approach combines physical accuracy with computational efficiency, making it suitable not only for scientific experiments but also for the practical design of modern telecommunications networks.

Simulations demonstrated that the simulator is capable of accurately reproducing key physical effects—dispersion, nonlinearity, amplifier noise, and the specifics of digital distortion compensation. A comparison of the obtained data with published results [1] confirmed a high degree of agreement: deviations in numerical calculations did not exceed 5–7%, demonstrating the reliability of the proposed method and the accuracy of the calculations.

The article established that the best transmission quality is achieved at a transmitter power level of 3–5 dBm, which minimizes errors and reduces the impact of nonlinear effects. It was also shown that the choice of modulation format significantly impacts system efficiency: QPSK and 16-QAM provide stable transmission with a moderate OSNR level, while 64-QAM requires higher values to maintain an acceptable BER level. Optimization of amplifier parameters, in particular the use of EDFAs with a pitch of approximately 80 km and a noise figure of no more than 5 dB, allows for stable channel operation. These results are consistent with the findings of [5] and confirm the need for comprehensive equipment configuration.

The practical value of this study lies in the fact that the simulator can be used as a tool for designing and optimizing next-generation optical networks. It enables the analysis of tradeoffs between transmission rate, energy efficiency, and noise immunity even before equipment deployment. Furthermore, this model can be used for educational purposes to demonstrate the operating principles of optical lines and study the influence of physical parameters on data transmission quality.

Further development of the simulator involves the incorporation of artificial intelligence elements to predict signal degradation parameters and automatically adapt line settings in real time. This will pave the way for the transition to intelligent optical network management systems and improve their performance and reliability.

Overall, it can be concluded that the developed simulator is an effective and flexible tool that helps accelerate the design and testing stages of optical communication systems, reducing the risk of errors and cutting the costs of physical experiments.

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