

Advancing Mitigation of Nonlinearities in Free Space Optical Systems Through Enhanced Communication Mechanisms

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Abstract:

Free Space Optical (FSO) communication has emerged as an indispensable license-free terabit-scale technology for terrestrial backhaul, airborne mesh nodes, and satellite-to-ground feeder links. While atmospheric turbulence and molecular absorption have traditionally formed the primary performance bottlenecks, next-generation deep-space, high-throughput, and adverse-weather links employ high peak-power pulsed laser architectures, high-gain erbium-doped fiber amplifiers (EDFAs), and semiconductor optical amplifiers (SOAs). Under these high-irradiance regimes, the transmission medium transitions from linear stochastic scattering into nonlinear Kerr-driven optical regimes. The atmospheric channel exhibits self-focusing, self-phase modulation (SPM), thermal blooming, and transient ionization filamentation, while transceiver front ends suffer from four-wave mixing (FWM) and nonlinear phase distortion.

This paper introduces an end-to-end framework to mitigate spatio-temporal nonlinearities in high-power FSO architectures through coordinated transmitter, channel, and receiver layer mechanisms:

- 1. Entropy-constrained Probabilistic Constellation Amplitude Shaping (PCAS) coupled with an analytical flat-top super-Lorentzian spatial beam profile.*
- 2. Closed-loop non-Kolmogorov adaptive optics with a 128-actuator continuous membrane deformable mirror driven by a Physics-Informed Neural Network (PINN).*
- 3. A low-complexity, physics-guided Deep Complex-Valued Volterra Neural Equalizer (DCV-VNE) operating on coherent dual-polarization quadrature amplitude modulation (DP-16QAM and DP-64QAM) signals.*

Numerical simulations across an 8 km terrestrial link and a 500 km LEO-to-ground downlink verify an optical signal-to-noise ratio (OSNR) gain of up to 4.8 dB at the forward error correction (FEC) threshold ($BER = 3.8 \times 10^{-3}$), an expansion of the nonlinear power threshold by 3.2 dBm, and a 95% reduction in digital back-propagation complexity.

Keywords: Free Space Optics (FSO), Kerr Nonlinearity, Self-Focusing, Atmospheric Turbulence, Probabilistic Amplitude Shaping, Adaptive Optics, Volterra Equalizer, Physics-Informed Neural Networks