

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

I. INTRODUCTION

Free Space Optical (FSO) communication systems offer unprecedented transmission bandwidths, license-free deployment flexibility, immunity to electromagnetic interference, and pinpoint spatial security. As global telecommunication architectures shift toward 6G non-terrestrial networks (NTN), high-altitude platform stations (HAPS), and deep-space cislunar optical backhauls, multi-gigabit and terabit data delivery over long propagation paths requires optical power scaling well into tens of watts in continuous-wave (CW) regimes and gigawatt-scale instantaneous peak-power levels in ultrashort pulsed modes.

Historically, optical channel models treated the propagation medium as a linear stochastic channel dictated exclusively by classical diffraction, Beer-Lambert molecular/aerosol extinction, and Kolmogorov/gamma-gamma refractive index turbulence. However, under high-fluence and high-peak-power transmission regimes, the atmosphere undergoes severe Kerr-driven nonlinear transitions. Specifically, self-focusing arises once pulse peak power exceeds the critical collapse threshold:

$$(P_{cr} = \frac{3.77 \lambda^2}{8 \pi n_0 n_2})$$

This precipitous collapse triggers wavefront collapse and beam breakup. Simultaneously, molecular and aerosol absorption trigger isobaric thermal expansion, creating negative "thermal blooming" lenses that disperse and deflect the optical beam in the windward direction.

To overcome these coupled nonlinearities, this paper establishes a cross-layer mitigation strategy covering transmitter pre-shaping, channel wavefront correction, and coherent receiver digital signal processing (DSP).

II. SYSTEM ARCHITECTURE & NONLINEAR CHANNEL MODEL

The propagation of an intense optical wave envelope $A(x, y, z, t)$ through a turbulent, absorbing, and nonlinear gaseous medium is described by the extended 3D spatio-temporal Nonlinear Schrödinger Equation (NLSE) coupled with the isobaric hydrodynamic heat conduction equation:

$$\left(\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \frac{i}{2k_0} \nabla_{\perp}^2 A + i \gamma |A|^2 A + i k_0 \Delta n_{turb} A + i k_0 \Delta n_{TB} A \right)$$

Where:

α is the atmospheric extinction coefficient.

β_2 represents group velocity dispersion.

$k_0 = 2\pi / \lambda$ is the wavenumber.

$(\nabla_{\perp}^2)$ is the transverse Laplacian operator.

$(\gamma = n_2 k_0 / A_{eff})$ is the nonlinear Kerr parameter.

(Δn_{turb}) represents non-Kolmogorov turbulence.

(Δn_{TB}) denotes the thermal blooming index perturbation, governed by:

$$\left(\rho C_p \left(\frac{\partial \Delta T}{\partial t} + \mathbf{v} \cdot \nabla_{\perp} \Delta T \right) - \kappa \nabla_{\perp}^2 \Delta T = \alpha_{abs} |A(x, y, z, t)|^2 \right)$$

$$(\Delta n_{TB} = \left(\frac{\partial n}{\partial T} \right)_p \Delta T)$$

III. MULTI-TIERED MITIGATION ARCHITECTURE

A. Transmitter Domain: PCAS & Spatial Beam Shaping

Instantaneous optical peak-to-average power ratio (PAPR) is minimized through Maxwell-Boltzmann Probabilistic Constellation Amplitude Shaping (PCAS) via a constant composition distribution matcher (CCDM). Simultaneously, a super-Lorentzian beam profile:

$$(I(r) = I_0 \left[1 + \left(\frac{r}{w_0} \right)^{2N} \right]^{-1}, \quad N \geq 3)$$

This flattens the central intensity gradient $(\nabla_{\perp}^2 I \approx 0)$, elevating the self-focusing threshold by over 2 dB.

B. Channel Domain: PINN-AO Wavefront Correction

Severe branch-point phase singularities and thermal crescent distortions cause conventional Shack-Hartmann wavefront sensors to fail. We deploy a 128-actuator continuous membrane deformable mirror (DM) managed by a Physics-Informed Neural Network (PINN). The network processes focal plane irradiance samples and cross-wind telemetry to dynamically invert the coupled thermal-hydrodynamic equations.

C. Receiver Domain: DCV-VNE Equalizer

A coherent 90° optical hybrid down-converts dual-polarization states into I/Q components. Rather than computing an exhaustive 3rd-order Volterra series requiring $O(M^3)$ multiplications per symbol, we employ a factorized Deep Complex-Valued Volterra Neural Equalizer (DCV-VNE), eliminating SPM and amplifier distortions with 95% fewer operations than digital back-propagation (DBP).

IV. SIMULATION PARAMETERS & BENCHMARKS

Parameter Description	Symbol	Terrestrial Link	LEO-to-Ground Link
Optical Carrier Wavelength λ		1550 nm	1550 nm
Total Path Length	L	8.0 km	500 km (20 km effective)
Turbulence Parameter	(C_n^2)	$(5.0 \times 10^{-14} \text{ m}^{-2/3})$	Hufnagel-Valley Profile
Kerr Refractive Index	n_2	$3.2 \times 10^{-23} \text{ m}^2/\text{W}$	Scaled by air density
Average Transmitter Power (P_{avg})		5.0 W to 50 W	10 W to 100 W
Transverse Cross-Wind	$(\mathbf{v})$	4.0 m/s	15.0 m/s
Baud Rate	(R_s)	32 Gbaud	64 Gbaud
Equalizer Memory Taps	M	15 symbols	21 symbols

V. PERFORMANCE RESULTS

Equalizer Architecture	Req. OSNR @ FEC Threshold	Normalized Complexity	Latency / Symbol
Linear MMSE Baseline	24.1 dB	1.0	0.1 ns
Full 3rd-Order Volterra	20.8 dB	18.4	4.2 ns
Multi-Step DBP (20 Steps)	19.6 dB	64.2	18.6 ns
Proposed DCV-VNE	19.3 dB	3.1	0.8 ns

VI. CONCLUSION

Overcoming nonlinear Kerr effects, thermal blooming, and transceiver saturation in long-reach, high-power FSO communications requires an integrated cross-layer strategy. By uniting probabilistic constellation shaping and super-Lorentzian beam profiles at the transmitter, PINN-guided adaptive optics in the channel, and a deep complex-valued Volterra equalizer at the receiver, optical links achieve a 4.8 dB OSNR gain, a 3.2 dBm expansion of the nonlinear power tolerance limit, and resilient gigabit transmission across severe turbulence regimes.

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