

Evaluation of Pulse Shapes on the Reception Performance of an FSO-WDM-PolSK System

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Abstract Free space optics (FSO) is a promising technology, enabling high-speed data transmission despite challenging and unpredictable atmospheric conditions. However, its performance remains highly dependent on the propagation environment and the type of optical pulse used. This present work analyzes the reception performance of FSO systems employing soliton microcombs with wavelength division multiplexing (WDM) and polarization shift keying (PolSK) modulation across various pulse profiles. The study focuses on comparison of the impact of pulse shaping namely Gaussian, Sech, Super-Gaussian, and Lorentzian profiles on key reception parameters such as Bit Error Rate (BER), received power, Q-factor, and eye diagram opening, under realistic atmospheric conditions including turbulence ($\sigma_R^2 = 0.35$) and pointing errors. Results reveal that the Sech-shaped microcombs consistently offer superior performance, with larger eye openings (± 2.5 A), higher received power (28.5 dBm), Q-factors exceeding 12.5, and BERs below 10^{-9} for a total generated bandwidth of ~ 12.5 THz, even under non-ideal alignment. The Gaussian profile follows closely, while Lorentzian and Super-Gaussian pulses exhibit significant performance degradation. The analysis also shows that optimizing receiver aperture diameter (40–60 cm) and beam divergence (0.25 mrad) enhances resilience to turbulence and alignment jitter. This study highlights the importance of pulse-profile design in soliton-based multi-wavelength FSO systems and provides actionable insights for optimizing waveform generation in spectrally efficient optical wireless links.

Keywords: Optical Free Space, reception performance, soliton, microcombs, pointing errors, pulse profiles

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1. Introduction

In recent years, the exponential growth of mobile data traffic fueled by the rise of multimedia applications and the widespread adoption of smart devices has placed unprecedented pressure on wireless communication infrastructure. Existing Radio Frequency (RF) and microwave systems are increasingly challenged in meeting the demands for high data rates, ultra-low latency, and reliable coverage. To address these limitations, Free-Space Optical (FSO) communication has emerged as a promising complementary solution, offering key advantages such as license-free operation, extremely high bandwidth, inherent physical-layer security, and immunity to electromagnetic interference [1,2]. These features position FSO links as strong candidates for next-generation wireless networks, particularly when high throughput and minimal interference are required. However, the performance and reliability of FSO systems are inherently tied to both system-level and

environmental factors. On the design side, parameters such as aperture diameter and beam divergence angle play critical roles in power collection and beam alignment. Externally, FSO links are highly sensitive to atmospheric effects such as fog, rain, dust, turbulence, scintillation, and multipath fading [3,4]. These impairments can lead to severe fluctuations in received power and induce bit errors if not properly mitigated. Consequently, future wireless communication architectures must integrate FSO technologies with robust design strategies including adaptive optics, optimized receiver geometries, and dynamic channel modeling to maintain performance across diverse deployment scenarios. With its ability to support high-capacity, low-latency links in spectrally congested environments, FSO stands at the forefront of enabling next-generation ubiquitous connectivity [5]. Recent advances in Free-Space Optical (FSO) communication have focused not only on overcoming atmospheric impairments but also on enhancing system capacity and resilience through architectural and modulation innovations. Among these, reception-side parameters such as aperture diameter, beam divergence, and pointing

accuracy has been shown to critically influence the Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and overall system robustness. Optimizing these parameters is essential for maintaining link quality, especially under turbulence and misalignment conditions [6]. To meet the growing demand for high-throughput links, Wavelength Division Multiplexing (WDM) has been widely adopted in FSO systems. WDM enables parallel transmission of multiple data streams, significantly increasing spectral efficiency. Recent studies have demonstrated the integration of optical frequency combs, particularly soliton microcombs, as highly stable and spectrally flat multi-wavelength sources for WDM-FSO architectures [7,8]. These microcombs, generated via micro-ring resonators, offer compactness, low phase noise, and tunable repetition rates, making them ideal for dense channel multiplexing in turbulent environments. In parallel, Polarization Shift Keying (PolSK) has emerged as a robust modulation technique for FSO links. By encoding information in orthogonal polarization states, PolSK enhances immunity to amplitude fluctuations and cross-channel interference. Comparative analyses have shown that PolSK outperforms traditional schemes like OOK and ASK in terms of BER under moderate to strong turbulence [9,10]. Moreover, its compatibility with WDM systems allows for scalable and spectrally efficient implementation. Despite these advancements, the combined impact of pulse shaping, microcomb generation, and reception geometry on system performance particularly under pointing errors remains underexplored. While some works have addressed the influence of beam divergence and aperture size on BER and eye diagram quality [6], few have investigated how different temporal pulse profiles (e.g., Gaussian, Sech, Super-Gaussian, Lorentzian) generated for soliton microcombs affect the reception dynamics in FSO-WDM-PolSK systems. In this context, the present study aims to evaluate the impact of soliton microcombs generated by various pulse shapes on key reception parameters including eye diagram opening, BER, and Q-factor in a WDM-PolSK FSO system subject to pointing errors. By bridging pulse shaping theory with practical receiver-side constraints, this work seeks to identify optimal waveform configurations that enhance system resilience and spectral efficiency under realistic deployment conditions. In what follows, we present the theoretical foundations of our work, in section 2 including soliton microcomb generation, pulse shape parameterization, and the modeling of atmospheric turbulence combined with pointing errors. In section 3, we expose and compare our results with the existing literature to highlight the influence of pulse profiles on reception quality in FSO systems. The section 4 is devoted to the conclusions on this present study.

2. Theoretical Background

2.1. Soliton Micro Combs Generation

The generation of soliton microcombs using micro-ring resonators marks a breakthrough in optical communications and integrated photonics. This process harnesses the complex interplay between Kerr nonlinearity and dispersion confinement, modeled by the Lugiato Lefever

equation (LLE). In its normalized form, the LLE describes the slow evolution of the intracavity field envelope $\Psi(t, \tau)$ where t is the slow time, describing the evolution of the field envelope over successive cavity round trips and τ is the fast time, a retarded time variable that resolves the field envelope within a single cavity round trip. The governing equation for the LLE is given by (1):

$$\frac{\partial \Psi}{\partial t} = -(1 + i\alpha)\Psi + i\frac{\partial^2 \Psi}{\partial \tau^2} + i|\Psi|^2\Psi + F \quad (1)$$

where α is the normalized detuning between the pump laser and the cavity resonance, the term $i\frac{\partial^2 \Psi}{\partial \tau^2}$ account for

group-velocity dispersion, $i|\Psi|^2\Psi$ represents Kerr nonlinearity, and F is the normalized pump amplitude [11]. With an appropriate balance of pump power and detuning, modulational instability evolves into a stable regime where dissipative Kerr solitons emerge. These solitons exhibit a temporal pulse shaped envelope and, in the frequency domain, form an equidistant comb defined by the resonator's free spectral range and soliton pulse duration [12]. Such microcombs have been experimentally realized in high-Q silicon nitride and crystalline resonators. Their integration at the chip scale enables a variety of photonic applications, including precise optical frequency references, high-speed broadband communication, and coherent data transmission within compact photonic circuits [13]. In this study, a pair of micro-ring resonators is cascaded in series, with each resonator engineered to operate at targeted resonance frequencies. Leveraging their intrinsic nonlinear characteristics, the system facilitates the generation of solitons within the optical domain. To further control and optimize spectral output, an integrated add/drop filter is employed as shown Figure 1, enabling precise selection and management of specific wavelengths produced by the resonator system.

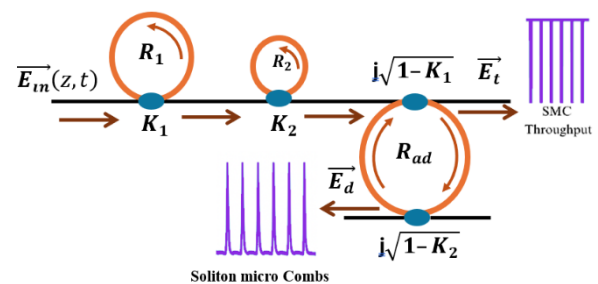


Figure 1. Schematic of a multi-resonator system for soliton micro-comb generation. The input field $E_{in}(z, t)$ is successively coupled into two micro-ring resonators ($R_1 = 50 \mu\text{m}$, $R_2 = 10 \mu\text{m}$) through the coupling coefficients K_1 and K_2 . An add-drop resonator ($R_{ad} = 150 \mu\text{m}$) allows extracting the signal either at the drop port (E_d) or at the throughput port (E_t). The generation of soliton micro-combs (SMC) results in periodic pulses in the time domain and a regularly spaced spectrum at the throughput port

In this study, we focus on four distinct pulse shapes, each playing a pivotal role in nonlinear optics and signal processing by shaping the propagation dynamics within the micro-resonators. These initial optical pulses are injected into the system through the first micro-ring resonator. We

considered Gaussian, super-Gaussian, hyperbolic secant, and Lorentzian, defined respectively by (2), (3), (4) and (5) [14,15]:

$$E_{in1}(z, t) = E_0 \exp\left[-\left(\frac{T}{T_0}\right)\right] \exp\exp\left(\frac{Z}{2L_D} - i\omega_0 t\right) \quad (2)$$

$$E_{in2}(z, t) = E_0 \exp\left[-\left(\frac{T}{T_0}\right)^{2n}\right] \exp\left(\frac{Z}{2L_D} - i\omega_0 t\right) \quad (3)$$

where $n \geq 2$, determines the sharpness of the pulse edges

$$E_{in3}(z, t) = E_0 \operatorname{sech}\left(\frac{T}{T_0}\right) \exp\left(\frac{Z}{2L_D} - i\omega_0 t\right) \quad (4)$$

$$E_{in4}(z, t) = \frac{E_0}{1 + \left(\frac{T}{T_0}\right)^2} \exp\left(\frac{Z}{2L_D} - i\omega_0 t\right) \quad (5)$$

Here, E_0 denotes the amplitude of the electric field, Z represents the position of the electromagnetic wave at time t along the propagation axis, L_D refers to the dispersion length characterizing pulse broadening, and ω_0 signifies the central (carrier) angular frequency of the pulse. In the micro ring resonator configuration examined, the injection of an optical pulse into the waveguide initiates resonance between the outputs of the two serially coupled rings. The normalized expression for the transmitted optical field following its propagation through a single resonator, accounting for both dispersive and nonlinear effects intrinsic to the device by (6) [8,16,17]

$$\left| \frac{E_{out}(t)}{E_{in}(t)} \right|^2 = (1 - \gamma) \times \left[1 - \frac{(1 - (1 - \gamma)x^2)k}{\left(1 - x\sqrt{1 - \gamma\sqrt{1 - k}}\right)^2 + 4x\sqrt{1 - \gamma\sqrt{1 - k}} \sin^2\left(\frac{\phi}{2}\right)} \right] \quad (6)$$

k denotes the coupling coefficient, and $x = \exp(L/2)$ represents the round-trip loss coefficient, where $L = 2\pi R$ is the length of the waveguide and α is the linear absorption coefficient. The total phase shift ϕ is the sum of the linear component $\Phi_0 = kLn_0$ and the nonlinear component $\Phi_{nl} = kLn_2E^2$, where E_n represents the amplitude of the input electric field. The output field from the first micro-ring resonator acts as the input to the second, which exhibits comparable wave propagation dynamics (6) [8]. After multiple round-trips in the first ring, strong Kerr nonlinearities and dispersive interactions generate a broadband, spectrally disordered output. This signal, once coupled into the second resonator, undergoes resonant spectral filtering that compresses its bandwidth. The resulting output shows enhanced temporal coherence and a markedly reduced Full Width at Half Maximum (FWHM), facilitating high-quality soliton microcomb formation. An add/drop filter is positioned at the output of the second ring to isolate and extract the soliton

microcombs. The mathematical expressions governing the optical field at the filter output are provided in (7), (8), where E_t denotes the impulse response of the throughput port and E_d corresponds to that of the drop port.

$$\left| \frac{E_t}{E_{in}} \right|^2 = \frac{(1 - K_1) - 2\sqrt{1 - K_1\sqrt{1 - K_2}} e^{-\frac{\alpha}{2}L} \cos(K_n L) + (1 - K_2) e^{-\alpha L}}{1 + (1 - K_1)(1 - K_2) e^{-\alpha L} - 2\sqrt{1 - K_1\sqrt{1 - K_2}} e^{-\frac{\alpha}{2}L} \cos(K_n L)} \quad (7)$$

$$\left| \frac{E_d}{E_{in}} \right|^2 = \frac{K_1 K_2 e^{-\frac{\alpha}{2}L}}{1 + (1 - K_1)(1 - K_2) e^{-\alpha L} - 2\sqrt{1 - K_1\sqrt{1 - K_2}} e^{-\frac{\alpha}{2}L} \cos(K_n L)} \quad (8)$$

2.2. Integration of PolSK Modulation with WDM Multiplexing Using Soliton Microcombs

In the proposed architecture, soliton microcomb generation Constitutes a foundational step for building high performance optical communication systems. These frequency combs are produced using micro-ring resonators operating in the anomalous dispersion regime, governed by the normalized Lugiato – Lefever Equation (LLE) (6) [11].

The resulting combs consist of equidistant spectral lines in the frequency domain, offering high coherence and exceptional temporal stability [18]. Each comb line serves as a stable optical carrier for data transmission. Prior to multiplexing, information is encoded individually onto each carrier using Polarization Shift Keying (PolSK), a modulation technique in which digital bits are represented by two orthogonal polarization states commonly horizontal and vertical [18,19]. Owing to its resilience against amplitude fluctuations and phase noise, PolSK is particularly suited for free-space optical (FSO) systems and integrated photonic platforms. To further enhance bandwidth utilization and increase overall system throughput, Wavelength Division Multiplexing (WDM) is employed [20,21]. In this scheme, each WDM channel corresponds to a distinct comb line, carrying an independent PolSK-modulated data stream. This integrated approach combining microcomb generation, vectorial PolSK modulation, and WDM multiplexing offers a scalable, energy-efficient, and robust solution for high-capacity optical communications in both FSO environments and chip-based systems.

2.3. Analysis of Pulse Shape Effects for PAOPR-Based Simulation

The Peak-to-Average Optical Power Ratio (PAOPR) is a essential metric for evaluating performance in optical communication systems, particularly with regard to signal integrity and transmission efficiency [22]. It measures the ratio between the maximum instantaneous optical power and the average effective power of a transmitted signal, offering valuable insight into its dynamic range and susceptibility to nonlinear distortion. The formal expression for PAOPR is provided in Equation (10), as originally defined in prior literature (9) [23,24]:

$$PAOPR = \frac{P_{peak}}{P} = [pr(a_k = 1) \cdot P_N]^{-1} \quad (9)$$

With P_{peak} the maximum optical power, $P_{peak} = P_N pr(a_k = 1)$ the average optical power transmitted, $pr(a_k = 1)$ the probability of transmitting a bit "1", and P_N the average optical power over a period T_b . In order to compare the performance of the different pulse shapes, the PAOPR increase factor is defined as follows by (10) [23,24]:

$$\Gamma_{PAOPR} = \frac{PAOPR}{PAOPR_{ref}} = \frac{1}{P_N} \quad (10)$$

Where $PAOPR_{ref}$ and $le PAOPR$ obtained with non-return-to-zero (NRZ) signalling and a rectangular pulse shape ($P_{Nref} = 1$). It is important to note that the Γ_{PAOPR} depends only on the characteristics of the pulse shape follows [23,24]. The value of Γ_{PAOPR} for the four analyzed pulse shapes are respectively defined by the following expressions:

- **Gaussian pulse:** the Γ_{PAOPRg} is given by (11):

$$\Gamma_{PAOPRg} = \frac{6}{\xi\sqrt{\pi}} \left[\operatorname{erf}\left(\frac{1}{\xi}\right) \right]^{-1} \quad (11)$$

$\operatorname{erf}(\cdot)$ is the error function.

- **Super Gaussian pulse:** the $\Gamma_{PAOPRsg}$ is given by (12):

$$\Gamma_{PAOPRsg} \approx \frac{1}{\xi} \quad (12)$$

- **Hyperbolic secant pulse:** the Γ_{PAOPRs} is given by (13):

$$\Gamma_{PAOPRs} = \frac{4}{\xi} \left[\tanh\left(\frac{1}{\xi}\right) \right]^{-1} \quad (13)$$

- **Lorentzian pulse:** the Γ_{PAOPRl} is given by (14):

$$\Gamma_{PAOPRl} = \frac{2}{\xi} \left[\frac{\xi}{1 + \xi^2} + \arctan\left(\frac{1}{\xi}\right) \right]^{-1} \quad (14)$$

where ξ is duty cycle of, $0 < \xi \leq 1$

For a same magnitude of duty cycle, for instance $\xi = 1$, $\Gamma_{PAOPR} \approx 34, 10, 40$ and 13 respectively for a Gaussian, a Super-Gaussian, a Lorentzian and a Secant hyperbolic pulse shape.

2.4. Mathematical Model of Turbulence with Pointing Error

To characterize the turbulence in our channel, we use the Gamma-Gamma model, which has a probability density function (PDF) that can be used to accurately model environments with low, medium and high turbulence. Its PDF is defined by (15) [25,26]:

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta}I) \quad (15)$$

where $K_P(x)$ is the modified Bessel function of the second kind, $\Gamma(x)$ is the Euler Gamma function, α is the effective

number of small-scale turbulences and β is the effective number of large-scale turbulences. The values of α and β are given by (16) and (17) [26].

$$\alpha = \left[\exp\left(\frac{0.49\sigma^2}{1+1.11\sigma^{12/5}}\right) - 1 \right]^{-1} \quad (16)$$

$$\beta = \left[\exp\left(\frac{0.51\sigma^2}{1+0.69\sigma^{12/5}}\right) - 1 \right]^{-1} \quad (17)$$

with σ^2 scintillation index, this parameter is essential for determining the nature of the turbulence in a given environment. It enables us to assess the strength of turbulence in an environment. its expression is given by (18) [26].

$$\sigma^2 = 1.23 C_n^2 k^{7/6} L_p^{11/6} \quad (18)$$

we have L_p the path length, k the wavenumber $k = \frac{2\pi}{\lambda}$ and C_n^2 the refractive index structure parameter. The Bit Error Rate (BER) is a critical metric for evaluating the performance of communication systems. It quantifies the likelihood of a bit being received incorrectly relative to the originally transmitted bit. Mathematically, BER is defined as the ratio of the number of erroneous bits to the total number of transmitted bits [27,28]. This parameter serves as a direct measure of system reliability and robustness, especially in the presence of noise, interference, and other channel impairments [21]. In this context, we consider Polarization Shift Keying (PolSK) as the modulation technique, where information is encoded in the polarization state of the optical signal [10,21]. The BER for the PolSK modulation format is given by the following expression The BER in the PolSK modulation format is represented by (19) [9,21]:

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{\sqrt{\gamma(I)}}{\sqrt{2}}\right) \quad (19)$$

For a given PolSK modulation scheme, with the duty cycle, the value of the signal-to-noise ratio is defined by (20) [29,30]:

$$\gamma = \frac{P \cdot \Gamma_{PAOPR} \cdot P_{I_0} \cdot R}{pr(a_k = 1) \cdot \sigma} \quad (20)$$

Where, P overall efficiency, P_{I_0} the input power, R is the responsivity of the photodetector and σ the noise, a function of turbulence. Then, we incorporate the pointing error into our model. The pointing effect is modeled as a multiplicative attenuation of the signal caused by misalignment. We introduce a random loss factor $h \in [0,1]$, with probability density given by (21):

$$f_{h_p}(h) = \frac{\zeta^2}{A_0^{\zeta^2}} h^{\zeta^2-1}. \quad (21)$$

Where:

— $0 \leq h \leq A_0$

— A_0 is the maximum loss in the absence of pointing

error (typically < 1)

— $\zeta = \frac{\omega_z}{\sigma_s}$, is the ratio between the beam radius at the

receiver and the standard deviation of the pointing jitter σ_s . We assume propagation over a distance L . The radius w_z of the beam in the plane of the receiver (in the presence of divergence θ) is written as $w_z = L \theta$.

Taking into account the pointing error, $\gamma(I)$ instantaneous SNR is given by (22)

$$\gamma(I) = \gamma I h. \quad (22)$$

According to (19) and (22), the BER is given by (23):

$$BER = \frac{1}{2} \operatorname{erfc} \left(\frac{\sqrt{\gamma I h}}{\sqrt{2}} \right) \quad (23)$$

The final distribution of the received intensity I is obtained as the multiplicative convolution of the Gamma-Gamma fading distribution and the pointing error distribution. [26,31,32,33,34]. It defined by (24)

$$P(I) = \int_0^{A_0} \frac{1}{h} f \left(\frac{I}{h} \right) f_{h_p}(h) dh \quad (24)$$

The instantaneous BER value as a function of channel turbulence is then given by (25) then (26):

$$P_{ec} = \int_0^\infty BER \times f_I(I) = \int_0^\infty \frac{1}{2} \operatorname{erfc} \left(\frac{\sqrt{\gamma(I)}}{\sqrt{2}} \right) \times P(I) dI \quad (25)$$

$$P_{ec} = \frac{1}{2} \int_0^{A_0} \int_0^\infty \operatorname{erfc} \left(\frac{\sqrt{\gamma(I)}}{\sqrt{2}} \right) \cdot \frac{1}{h} f \left(\frac{I}{h} \right) f_{h_p}(h) dh dI \quad (26)$$

To facilitate the resolution of Equation (26), the complementary error function $\operatorname{erfc}(x)$ and the modified Bessel function of the second kind $K_p(x)$ are replaced by their representations in terms of the Meijer G-function [35], defined respectively by (27) and (28):

$$\operatorname{erfc}(\sqrt{x}) = \frac{1}{\sqrt{\pi}} G_{2,0}^{1,2} \left(x \middle| \begin{matrix} 1 \\ 0, 1/2 \end{matrix} \right) \quad (27)$$

$$K_\nu = \frac{1}{2} G_{0,2}^{2,0} \left(\frac{x^2}{4} \middle| \begin{matrix} - \\ (v-2), -(v-2) \end{matrix} \right) \quad (28)$$

Based on the integral formula for the product of Meijer G-functions as described in [35], the result of evaluating the integral for the PolSK modulation is given by (29):

$$P_{ec} = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}} \zeta^2 (A_0)^{\frac{\alpha+\beta}{2}-1}}{4\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} G_{2,4}^{3,1} \left(\frac{\alpha\beta\gamma A_0}{8} \middle| \begin{matrix} 1, 1-\frac{\alpha+\beta}{2} \\ \frac{1}{2}, \zeta^2 - \frac{\alpha+\beta}{2}, \zeta^2 - 1, 0 \end{matrix} \right) \quad (29)$$

3. Results and Discussions

3.1. Results

3.1.1. Soliton Micro Combs (SMCs) Generation

An optical pulse Gaussian, Super-Gaussian, Hyperbolic Secant (Sech) or Lorentzian profile is inputted into the first ring. The rings are characterized by the following parameters power of 500 mW, and central wavelength $\lambda_0 = 1550$ nm, $K_1 = K_2 = 0.85$, $n_0 = 3.34$ (InGaAsP/InP), $A_{eff} = 25 \mu m^2$, $\alpha = 0.5$ dB.mm⁻¹, $\gamma = 0.05$, $n_2 = 3.2 \times 10^{-17}$ m²/W. Each input profile induces chaotic time-domain signals in the first ring (R_1). The second ring (R_2) acts as a filter, suppressing chaos, while the add/drop filter extracts stable temporal solitons. Figure 2, Figure 3, Figure 4 and Figure 5 illustrate the multi-soliton generation process, revealing that the broadband signal originates within the first ring resonator R_1 . In contrast, resonator R_2 serves as a spectral filter, compressing the bandwidth and reducing the group velocity. The key stages include: (a) input soliton pulse, (b) spectral broadening, (c) bandwidth compression and filtering in R_2 , and (d) temporal soliton.

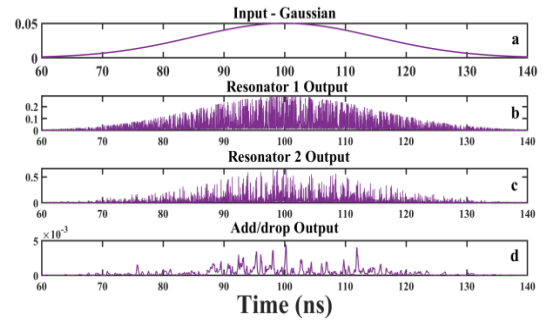


Figure 2. temporal Soliton generation, (a) Input pulse Gaussian, (b) Chaotic signals output R1, (c) Filtered signals out- put R2, Temporal soliton output add/drop

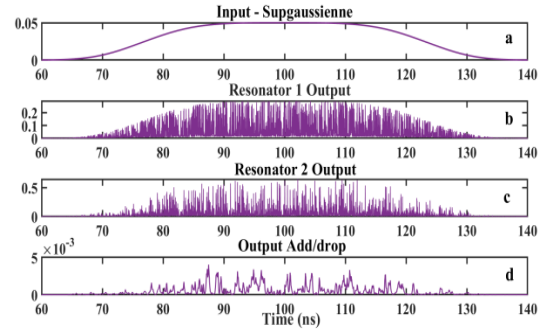


Figure 3. temporal Soliton generation, (a) Input pulse Super- Gaussian, (b) Chaotic signals output R1, (c) Filtered signals output R2, Temporal soliton output add/drop

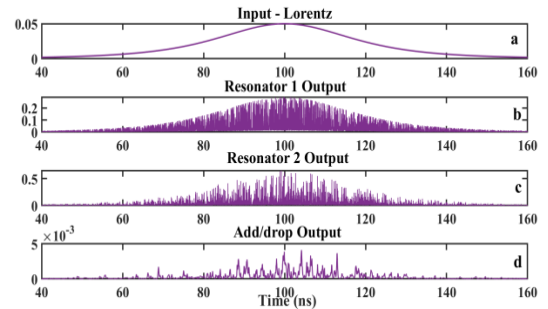


Figure 4. temporal Soliton generation, (a) Input pulse hyperbolic Secant, (b) Chaotic signals output R1, (c) Filtered signals output R2, Temporal soliton output add/drop

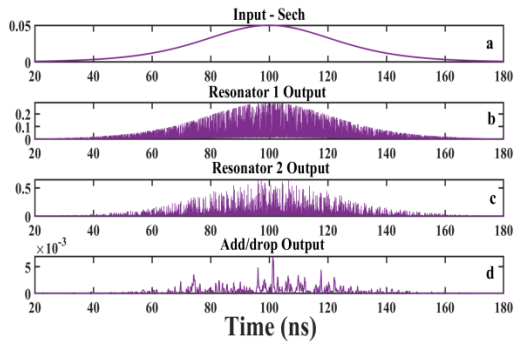


Figure 5. temporal Soliton generation, (a) Input pulse Lorentzian, (b) Chaotic signals output R1, (c) Filtered signals output R2, Temporal soliton output add/drop

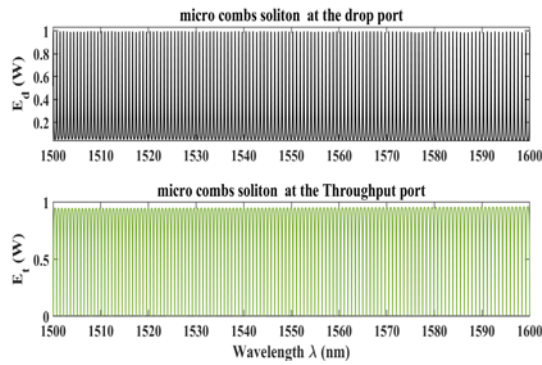


Figure 6. Spectra of soliton micro-combs generated at the drop port (E_d) and throughput port (E_t) of the add-drop resonator. The evenly spaced spectral lines confirm the generation of soliton micro-combs, which can be exploited for multi-channel optical communications

Among the evaluated pulse profiles, the Sech pulse exhibits the broadest spectral expansion, outperforming Gaussian, super-Gaussian, and Lorentzian shapes. It generates temporal solitons with the most favorable Full Width at Half Maximum (FWHM) of approximately 0.105 ns, corresponding to a spectral width of 9.5 GHz. The add/drop filter enforces frequency-domain mode structuring, delivering consistent output regardless of the input pulse shape. The Free Spectral Range (FSR), precisely measured at 95.3024 GHz, is dictated by the resonator geometry and plays a crucial role in mode selection and soliton dynamics. According to Figure 6, the Sech pulse produces 132 soliton micro-combs across the 1500 – 1600 nm wavelength range at both the drop and through ports, yielding a total bandwidth of $\Delta_f \approx 12.5$ THz. The

hyperbolic secant (Sech) pulse profile offers superior performance in soliton microcomb generation, as it naturally satisfies the equilibrium conditions required for dissipative Kerr solitons in the anomalous dispersion regime [12]. This configuration enhances spectral efficiency, optimizes available bandwidth, and supports effective wavelength division multiplexing (WDM), thereby reducing inter-channel interference and increasing carrier capacity within the same bandwidth envelope.

3.1.2. Effect of receiver's Aperture Diameter

In FSO communication, the receiver aperture diameter plays a crucial role in deciding the optical power collected at the receiver. A larger aperture improves the system's ability to capture optical signals, especially in the existence of beam divergence and atmospheric turbulence [6]. As can be seen in Figure 7 BER decreases almost exponentially as the diameter of the receiving lens increases, thanks to better power collection and therefore a higher SNR. As expected, as the diameter increases, so does the received power (P_{rec}), rising from 10 dBm to 27–28 dBm for the best profiles. This improvement stems from the fact that a larger receiver diameter collects more incident optical power due to its greater surface area. This directly enhances the geometric gain, thereby improving the overall power budget at the receiver end. As Figure 8 indicates, among the shapings studied, the Sech profile consistently has the lowest BER and the highest received power (up to ~ 28.5 dBm at 50 cm), followed very closely by the Gaussian (~ 27.5 dBm), while the Lorentzian and super-Gaussian profiles suffer from greater losses at the periphery and display P_{rec} of ~ 23 dBm and 22 dBm respectively, as well as higher BERs (the super-Gaussian peaking at around 10^{-4} for large diameters). Beyond 50–60cm, the improvement in BER and power is marginal, which suggests that a receiver diameter of 40–60cm and Sech shaping should be preferred to optimize the cost/performance trade-off in FSO WDM-PolSK links under moderate turbulence ($\sigma_R^2 = 0.35$). This is because a larger receiver diameter collects more incident optical power due to its greater surface area, which directly enhances the geometric gain and improves the overall power budget. However, past a certain threshold, this gain saturates, making further increases less effective, while disproportionately increasing system complexity and cost.

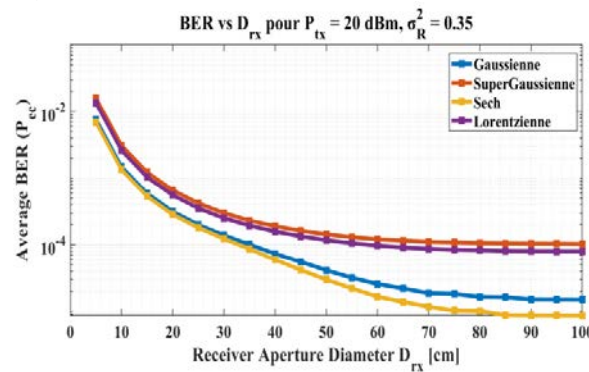


Figure 7. Average bit error rate (BER) versus receiver aperture diameter D_{rx} for a transmitted power $P_{tx} = 20$ dBm and scintillation index $\sigma_R^2 = 0.35$). Four beam profiles (Gaussian, Super-Gaussian, Sech, and Lorentzian) are compared. Increasing the receiver aperture diameter reduces the BER, with the Sech profile showing the most significant improvement

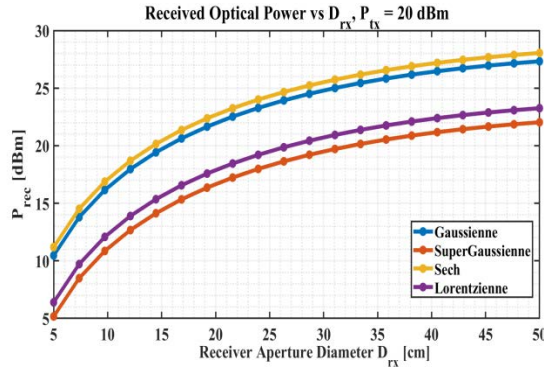


Figure 8. Received optical power P_{rec} as a function of the receiver aperture diameter D_{rx} for a transmitted power $P_{tx} = 20$ dBm. Larger receiver apertures significantly improve the collected power. The Sech profile achieves the highest received power, followed by the Gaussian profile

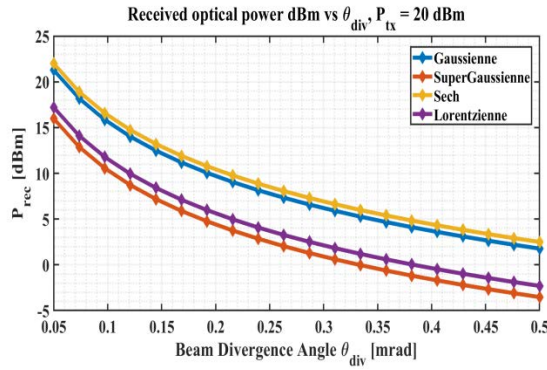


Figure 9. Received optical power P_{rec} as a function of the beam divergence angle θ_{div} for a transmitted power $P_{tx} = 20$ dBm. Increasing beam divergence leads to a rapid decrease in received power. The Sech profile maintains higher received power compared to the other beam profiles

3.1.3. Effect of Beam Divergence Angle

It is evident from Figure 9 The received power diminishes rapidly as the divergence angle increases, with pulse profiles ranked from best to worst performance as follows: Sech > Gaussian > Lorentzian > Super-Gaussian. The Lorentzian and Super-Gaussian profiles are penalized by, respectively, overly extended wings and excessively wide plateaus, which scatter significant energy outside the receiver aperture. As Figure 10 depicted, average BER exhibits an inverted U- shaped trend, elevated levels ($<10^{-2}$) are observed at very low divergence angles (<0.1 mrad), driven by turbulence and pointing jitter, minimal values (10^{-7} – 10^{-6}) occur near $0.20 - 0.27$ mrad due to effective aperture averaging, and BER rises again ($>10^{-3}$) beyond 0.35 mrad, primarily due to degraded SNR from insufficient received power. This situation is attributed to the high beam divergence at such angles, significantly reducing the power density at the receiver aperture. Since the aperture diameter remains fixed, an increasing portion of the transmitted energy is no longer captured, diminishing the usable power budget.

As a consequence, the received signal becomes more susceptible to thermal noise and atmospheric fluctuations, limiting the system's ability to accurately decode the transmitted symbols. This energy deficit undermines the robustness of the FSO link, despite partial mitigation of scintillation effects.

Among all profiles, Sech and Gaussian pulses yield the lowest BERs at optimum divergence, with Lorentzian trailing slightly and Super-Gaussian consistently underperforming. Consequently, a divergence angle of approximately 0.25 mrad, combined with a Sech pulse,

represents the most effective compromise among divergence, received power, and turbulence resilience. Experimental results corroborate that FSO systems with narrower divergence angles deliver superior performance provided that beam tracking remains precise [36]. Dynamically adjust the divergence or modify the transmitter/receiver diameter according to atmospheric conditions to optimize the reception parameters of the FSO- WDM- PoLSK link.

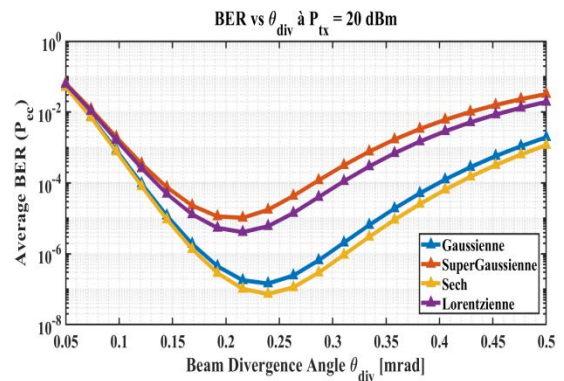


Figure 10. Variation of the average BER as a function of the beam divergence angle θ_{div} at $P_{tx} = 20$ dBm An optimal θ_{div} value minimizes the BER, illustrating the trade-off between reducing scintillation and avoiding excessive coupling losses. The Sech profile provides the best overall performance.

3.1.4. Eye diagram Analysis

The analysis of pulse shapes through their associated eye diagrams reveals marked disparities in terms of noise robustness, temporal stability, and sensitivity to intersymbol interference (ISI). As highlighted in Figure 11,

the Gaussian profile stands out with a wide vertical opening ($\pm \approx 2A$) and a generous horizontal aperture ($\sim 0.5T_s$), indicating a high noise margin, low timing jitter, and well-controlled ISI due to its balanced spectral response. The Super-Gaussian

profile, in contrast, exhibits a reduced vertical opening ($\pm \approx 4.5A$) and a slightly narrower horizontal span ($\sim 0.4T_s$).

Table 1. Input parameters

Input parameters	Descriptions	Values
σ	Noise	10^{-7} A/Hz
σ_R^2	Rytov variance	0.35
σ_s	Jitter	0.25 m
P	power	20 dBm
M	PolSK Modulation order	32
D_{rx}	Receiver aperture diameter	5 - 100 cm
θ_{div}	Beam Divergence angle	0.05-0.5 mrad
R	Responsivity	0.5 A/W

While its sharper transitions enhance timing precision, they come at the cost of lower amplitude and diminished resilience to channel impairments. The sech (hyperbolic secant) profile provides the most advantageous configuration, combining a superior vertical eye opening ($\pm \approx 2A$) with a horizontal width comparable to that of the Gaussian ($\sim 0.5T_s$). This makes it an optimal trade-off between energy efficiency and ISI mitigation. Conversely, the Lorentzian profile shows the weakest performance, characterized by a limited vertical aperture ($\pm \approx 0.7A$) and a very narrow horizontal opening ($< 0.3T_s$), symptomatic of significant timing jitter and temporal spreading caused by its long-tailed impulse response. Notably, the sech profile's larger eye opening directly correlates with enhanced signal quality, as evidenced by a high Q-factor (~ 12.5) and clear logical level separation, yielding a bit error rate (BER) below 10^{-9} . This extremely low BER confirms excellent transmission fidelity, with negligible bit-level impairments. From a receiver design perspective, optimizations such as increasing the receiver aperture diameter and reducing the beam divergence angle significantly enhance collected power, thereby improving the vertical eye opening (through higher SNR) and reducing jitter-induced sampling uncertainty.

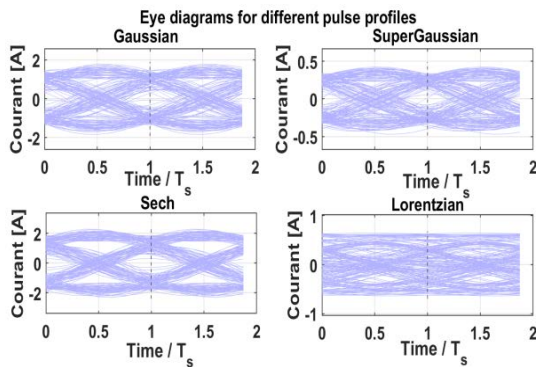


Figure 11. Eye diagrams for different pulse profiles (Gaussian, Super-Gaussian, Sech, Lorentzian). The eye openings indicate transmission quality and robustness to noise. The Sech profile shows a wider and clearer eye diagram, confirming its superior transmission performance

3.2. Discussions

The generation of soliton microcombs presents substantial advantages for free-space optical (FSO) communication systems, particularly in terms of spectral efficiency and energy conservation [23,37]. Their inherent propagation stability makes solitons ideal for mitigating the adverse effects of atmospheric turbulence and dynamic channel conditions. In this study, microcombs are generated using micro-ring resonators, which play a pivotal role in producing coherent and stable solitonic waveforms. These structures offer strong optical confinement and tunability across narrow frequency bands. Key parameters such as Free Spectral Range (FSR) and Full Width at Half Maximum (FWHM) are precisely controlled [38], enabling tailored frequency structuring and consistent mode formation. Significantly, the hyperbolic secant (Sech) pulse profile proves optimal for initiating soliton microcomb generation. As demonstrated by [39], this pulse shape naturally satisfies the equilibrium conditions required by dissipative Kerr solitons in the anomalous dispersion regime, maintaining a stable balance between dispersion and Kerr nonlinearity. The FWHM, a defining parameter of the Sech pulse, directly supports the formation of solitons and enhances comb stability. Micro-ring resonators further facilitate miniaturization, allowing integration into compact and energy-efficient platforms without sacrificing performance [38,40]. This methodology aligns with prior validated designs coupling ring resonators with add/drop filters [8], enabling precise control over FSR and FWHM and enhancing system-level efficiency. Both FSR and FWHM are crucial for ensuring high-quality optical transmission. A well-defined FSR enables dense wavelength division multiplexing (DWDM), expanding channel capacity while minimizing spectral overlap [41]. A narrow FWHM improves wavelength discrimination, reducing inter-channel interference and preserving signal integrity even under turbulent transmission conditions. To ensure compliance with ITU-T DWDM standards (G.694.1), the comb is confined to the standard C+L band (1530–1625nm), avoiding extended S or U bands that require non-standard components. The 1550nm transmission window ($\sim 193\text{THz}$), central to the comb spectrum, offers low fog attenuation and supports Class 1 eye-safe operation at elevated powers [42,43,44]. This facilitates long-range, low-risk communication links. Widely adopted technologies such as InP-based lasers and EDFLs, while moderately priced, remain highly compatible with this spectral band [42,45]. To harness the full spectral and spatial capacity of the generated microcombs, the modulation scheme is critically selected. As highlighted in [46], adaptation to source characteristics is essential for maintaining optimal channel performance. In this context, Polarization Shift Keying (PolSK) modulation is employed during the early characterization phase due to its robustness against polarization-mode distortion and atmospheric fluctuations [9,47]. PolSK encodes data using orthogonal polarization states, enabling dense information mapping onto individual comb lines with high spectral compactness. Upon successful validation under PolSK, the system transitions to full-scale operation using Wavelength Division Multiplexing (WDM). Each comb line serves as

an independent carrier within a tightly spaced optical grid, leveraging the fine spectral structuring and stability of the soliton combs to maximize throughput and channel utilization. This combined PolSK-WDM approach ensures a flexible and resilient framework for high-capacity, turbulence-tolerant FSO communication systems. Building on the spectral and structural advantages conferred by soliton microcomb generation, it becomes essential to examine how receiver-side parameters influence overall system performance. Among these, the receiver's aperture diameter plays a pivotal role in determining signal collection efficiency and spatial coupling under turbulent conditions. About the effect of Receiver's Aperture Diameter, our results quantitatively confirm and refine the central role of receiver optics and beam shaping in free-space optical (FSO) communication links, in strong agreement with both foundational and recent literature. Increasing the receiver aperture diameter significantly enhances the received power (P_{rec}), with a gain of approximately 17 dB between 5 cm and 50 cm for instance, from ~ 11 dBm to ~ 28 dBm with a Sech beam profile. This gain is attributed to the aperture averaging effect, which allows a larger portion of the beam to be collected, thereby mitigating the impact of scintillation and beam wander. This trend is well documented, notably by [48], and validated by NASA field measurements over a 4.5 km link, where increasing P_{rec} from 10 to 25 dBm reduced the BER from $\sim 10^{-2}$ to $\sim 10^{-9}$ [49]. More recently, [50] demonstrated that increasing the receiver diameter under moderate turbulence improves BER up to a saturation point, while [51] proposed an optimization method for aperture sizing to enhance link robustness. Beyond 40–50 cm, the growth in P_{rec} slows significantly, as most of the optical spot is already captured, making further gains marginal. This saturation effect has been observed experimentally by [52] and numerically by [53], who reported a BER drop from $\sim 10^{-2}$ to $\sim 10^{-9}$ for a partially coherent Gaussian beam as the aperture increased from 5 to 30 cm. This improvement in P_{rec} directly translates into a marked reduction in bit error rate (BER), due to a higher photon signal-to-noise ratio. Beam profile also plays a critical role, the Sech profile yields the best performance, combining maximum received power (~ 28.5 dBm at ~ 50 cm) with minimal BER ($\sim 5 \times 10^{-5}$) thanks to its optimal trade-off between central intensity and peripheral losses, as supported by several beam shaping studies [26]. In contrast, Lorentzian and super-Gaussian profiles, which are more spread out or have broader wings, suffer from aperture losses ($P_{rec} \sim 23$ dBm and ~ 22 dBm, respectively) and exhibit higher BERs up to 4×10^{-4} . Recent work by [54] also showed that dynamic beam shaping can maintain $BER < 4 \times 10^{-7}$ in indoor FSO environments, while [55] proposed adaptive beamwidth control using intelligent reflecting surfaces (IRS) to improve pointing error tolerance. In the context of high-speed WDM-PolSK systems, these receiver parameters are essential for optimizing link design. In summary, our results provide a fine-grained numerical validation of known experimental and theoretical trends, while offering concrete recommendations for system design under moderate turbulence ($\sigma_R^2 = 0.35$) notably, adopting a receiver

diameter between 40 and 60 cm and a Sech or slightly Gaussian beam profile. While aperture diameter governs the receiver's ability to capture incident optical energy, the effectiveness of this process is intricately linked to the beam divergence angle. A comprehensive understanding of how divergence affects beam footprint, alignment tolerance, and spatial dispersion further enriches the optimization strategy for FSO link design. Regarding The effect of Beam Divergence Angle, our results align closely with existing literature and unveil practical opportunities for system optimization through adaptive divergence strategies and judicious pulse profile selection. Specifically, they underscore an optimal divergence angle near 0.25 mrad, where the bit error rate (BER) reaches a minimum ($\sim 10^{-7}$) while preserving sufficient received power. This value corroborates recommendations found in prior studies. [56] demonstrated that, for short-range untracked optical links, divergences of several tenths of a milliradian enhance robustness without necessitating active beam tracking. Similarly, [57] emphasized the benefits of Variable-Beam Divergence Angle (VBDA) techniques, which adaptively modulate the beam between 0.1 and 1 mrad to balance scintillation effects and atmospheric attenuation. Our performance curves reinforce the superior efficiency of the Sech pulse profile, which slightly outperforms Gaussian pulses and significantly surpasses the super-Gaussian, echoing the findings of [58,59]. These works revealed that moderate-wing profiles better exploit aperture averaging mechanisms than those with extended plateaus. Moreover, our identified optimal divergence remains comfortably below the maximum tolerable limit up to 15 mrad under turbulent conditions outlined by [60] to maintain a target BER of 10^{-9} , providing a valuable margin of resilience against atmospheric fluctuations. On a practical front, these findings advocate the deployment of adaptive beam control mechanisms capable of tuning divergence angles between 0.15 and 0.35 mrad, contingent on scintillation and pointing jitter. Preference should be given to Sech or Gaussian profiles, with partially coherent beams also considered to further suppress scintillation. Finally, a moderate increase in receiver aperture diameter can ease divergence constraints without degrading BER an approach validated by numerous studies on long-distance aperture averaging.

4. Conclusion

This study investigated the impact of soliton microcomb generated pulse shapes on the reception performance of FSO-WDM-PolSK systems under atmospheric turbulence and pointing errors. Among the evaluated profiles, the sech (hyperbolic secant) pulse emerged as the most effective, yielding the most robust microcomb structure with a FWHM of 0.105 ns and a FSR of 95,30 GHz. Its spectral footprint supports a total comb bandwidth of $\Delta f \approx 12.5$ THz, assuming a fixed repetition rate spacing (FSR), making it ideally suited for dense WDM transmission. The sech profile consistently demonstrated superior reception metrics: highest received power (28.5 dBm), widest eye opening ($\pm 2.5A$), a Q-factor above 12.5, and BERs below 10^{-9} , even under

moderate turbulence ($\sigma_R^2 = 0.35$) and misalignment conditions. The Gaussian profile offered stable performance with slightly reduced capacity, while Lorentzian and Super-Gaussian pulses showed lower resilience, suffering from energy spreading and greater susceptibility to jitter and ISI. Moreover, the results underline the importance of optimizing receiver geometry. A diameter of 40–60 cm and a beam divergence around 0.25 mrad proved to be the most effective configuration, balancing received power, BER, and system complexity. In summary, sech-shaped microcombs, coupled with carefully tuned reception parameters, offer a powerful strategy for deploying high-capacity, turbulence-resilient FSO-WDM-PolSK links in practical scenarios. Future work will build upon the sech-shaped pulse format, leveraging its spectral compactness and resilience to nonlinear distortions to further enhance system robustness under dynamic channel conditions.

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