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Comparative Study of the O–U-Band Transmission Performance of Different Optical Fiber Links Based on the GN Model

Bingyan Shan ¹, Jingyang Tian ¹, Xiaojian Li ¹, Qianle Huang ¹, Mengfei Huo ¹ and Bing Lei ^{2,*}

¹ School of Electrical, Electronic and Mechanical Engineering, University of Bristol, Bristol BS8 1TR, UK; shanbingyan@mail.nwpu.edu.cn (B.S.); tianjingyang456@gmail.com (J.T.); 7421235063liqifu@gmail.com (X.L.); h1194351451@gmail.com (Q.H.); huomengfei7@gmail.com (M.H.)

² College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China

* Correspondence: leibing_2000@nudt.edu.cn

Abstract

As the available spectrum in the conventional C band becomes increasingly limited, ultra-wideband transmission across the O–U wavelength range (1260–1675 nm) provides a promising approach to increasing optical fiber link capacity. To support performance evaluation and preliminary fiber-link selection, this study compares standard single-mode fiber (SMF), pure-silica-core fiber (PSCF), and hollow-core fiber (HCF) links across the O–U bands. A transmission-performance analysis framework was established based on the Gaussian noise (GN) model. Band-specific amplifier parameters and fiber-specific span configurations were incorporated to evaluate transmission reach, optimum launch power, and theoretical capacity. Auxiliary simulations were conducted using VPIphotonics Design Suite 11.1 (VPIphotonics GmbH, Berlin, Germany) for representative C-band cases to examine the consistency of the overall trends predicted by the theoretical analysis. The GN-model analysis and auxiliary simulations show consistent overall trends, indicating that the GN model can serve as a computationally efficient tool for comparative link assessment and preliminary fiber-link selection. Under the unified analytical framework and consistently defined engineering constraints, PSCF offers a clear transmission-reach advantage over conventional SMF, whereas HCF shows greater theoretical power tolerance and capacity potential under the adopted representative parameter assumptions. Under the adopted non-saturated reference operating conditions, the per-channel capacity of HCF is approximately 34–54% higher than that of SMF in the S, C, L, and U bands and also clearly exceeds that of PSCF. These HCF results should be interpreted as model-based theoretical estimates, since practical performance may be affected by loss, dispersion uncertainty, splice/connector loss, bending sensitivity, and mode coupling.

Keywords: optical fiber link performance evaluation; Gaussian noise model; O–U bands; ultra-wideband transmission; standard single-mode fiber; pure-silica-core fiber; hollow-core fiber

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1. Introduction

With the continuously increasing demand for per-fiber transmission capacity, the available spectrum of the conventional C band has become increasingly insufficient to

support the development of ultra-wideband optical fiber communication systems. Extending the transmission window beyond the C and L bands to encompass O–U wavelength range (1260–1675 nm, covering the O, E, S, C, L, and U bands) is therefore an important approach to improving spectral utilization and link capacity [1]. However, the performance of O–U-band links is determined not only by the available bandwidth but also by the combined effects of chromatic dispersion, attenuation, nonlinear effects, and the gain and noise characteristics of amplifiers operating in different bands [2]. Accordingly, comparing the transmission reach and capacity characteristics of different fiber links within a consistent engineering framework is of practical importance for ultra-wideband link design and fiber selection.

In this study, standard single-mode fiber (SMF), pure-silica-core fiber (PSCF), and hollow-core fiber (HCF) are selected for comparison. SMF is the most widely deployed reference fiber in current optical communication systems. PSCF exhibits relatively low attenuation and a large effective mode area, offering advantages for long-haul transmission [3]. By guiding light through a hollow core, HCF substantially reduces material nonlinearity and therefore has considerable potential for high-power and high-capacity transmission [4]. Beyond these fiber solutions, multimode fiber transmission has also been investigated as an alternative route for capacity scaling, although its practical performance is strongly affected by mode coupling, modal dispersion, steady-state power redistribution, and temperature-dependent perturbations [5,6]. In addition, bending resistance and temperature sensitivity remain important practical considerations for optical-fiber and HCF-based systems [7,8]. These three fiber types represent conventional solid-core fiber, low-loss large-effective-area solid-core fiber, and low-nonlinearity hollow-core fiber solutions, respectively, making them suitable representative candidates for comparing link performance across the O–U bands.

Accordingly, this study establishes a framework based on the Gaussian noise (GN) model [9] for analyzing the O–U-band link performance of SMF, PSCF, and HCF, and compares the transmission characteristics of the three fiber links within a unified analytical framework and under consistently defined engineering constraints. The central question addressed in this study is whether each fiber type is better suited to long-haul or high-capacity transmission across the O–U bands under consistently defined amplifier constraints and fiber-specific span configurations. The results are intended to provide a reference for the performance comparison and preliminary selection of different fiber links for O–U-band transmission systems. Because the analysis relies on model-based fiber and amplifier parameters, the conclusions are presented as comparative trends under the adopted assumptions rather than as absolute deployment limits for practical O–U-band systems.

2. Parameter Configuration and GN Model

2.1. Fiber and Amplifier Parameters

SMF, PSCF, and HCF were selected for comparison, and their performance across the O–U bands was evaluated within a unified comparison framework using consistently defined link constraints. As ultra-wideband link performance is jointly affected by chromatic dispersion, attenuation, and nonlinear effects, the chromatic dispersion coefficient D , attenuation coefficient α , and nonlinear coefficient γ were adopted as the principal input parameters for the three fiber types. These parameters determine the accumulated chromatic dispersion, span loss, and strength of Kerr nonlinear interference in the link, respectively, and thus form the basis for the subsequent GN-model calculations of transmission reach and capacity. To improve the transparency and reproducibility of the parameter configuration, the band-specific fiber parameters used in the GN-model calculations are explicitly summarized before the reach and launch-power analyses.

The chromatic dispersion coefficient is determined by the wavelength dependence of the effective refractive index and can be expressed as follows [10]

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2}, \quad (1)$$

where λ is the operating wavelength, c is the speed of light in vacuum, and n_{eff} is the effective refractive index of the fiber. For SMF, the dispersion parameters were determined using the Sellmeier equation and empirical fitting relationships [11]. For PSCF, the contribution of waveguide dispersion was additionally considered together with material dispersion, and the effective mode area and nonlinear coefficient were calculated based on the mode-field-radius relationship [12,13]. For HCF, the conventional Sellmeier relationship for solid-core fibers is not directly applicable because the optical field is predominantly distributed within the air core. Therefore, the effective refractive index was estimated using the poor-man's model [14]

$$n_{\text{eff}} = 1 - \frac{1}{8} \frac{u_{01}^2 \lambda^2}{\pi^2 R_{\text{eff}}^2}, \quad (2)$$

where u_{01} is the first zero of the zeroth-order Bessel function J_0 , λ is the operating wavelength, and R_{eff} is the effective core radius. The dispersion parameters of HCF in the different transmission bands were then obtained accordingly.

Link loss and nonlinear effects are characterized by the attenuation coefficient α and nonlinear coefficient γ , respectively. In this study, the attenuation parameters of SMF and PSCF were determined based on established loss models and fitted parameters, whereas those of HCF were configured with reference to previously reported theoretical and experimental results [15]. The nonlinear coefficient, which characterizes the strength of Kerr nonlinear effects, can be expressed as follows [12,16]

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}, \quad (3)$$

where n_2 is the nonlinear refractive index and A_{eff} is the effective mode area. The relatively large effective mode area of PSCF contributes to a lower nonlinear coefficient. In HCF, the optical field is primarily confined within the air core, resulting in an effective nonlinear coefficient that is substantially lower than those of solid-core fibers. The nonlinear coefficient of HCF was set based on previously reported high-speed transmission experiments [17]. It should be noted that the HCF parameters adopted here represent a model-based reference scenario compiled from reported HCF characteristics and simplified dispersion/loss modeling, rather than the measured full-O–U-band performance of a single commercially available HCF. Together, the D , α , and γ values serve as input parameters for the subsequent GN-model calculations. The band-averaged dispersion parameter β_2 , attenuation coefficient, nonlinear coefficient, and span length used in the reach calculations are summarized in Table 1, while the underlying model coefficients are retained in Appendix A.

Table 1. Band-specific fiber parameters used in the GN-model reach calculations.

Fiber	Band	Wavelength Range (nm)	β_2 (ps ² /km)	α (dB/km)	γ (W ^{−1} km ^{−1})	Span Length (km)
SMF	O-low	1260–1300	2.5883	0.4150	2.3620	65
SMF	O-high	1330–1360	−2.3292	0.3475	2.0245	65
SMF	E	1360–1460	−7.6358	0.2988	1.7612	65
SMF	S	1460–1530	−14.9669	0.2489	1.4615	65
SMF	C	1530–1565	−19.8612	0.2311	1.3088	65
SMF	L	1565–1625	−24.6800	0.2365	1.1925	65
SMF	U	1628–1655	−29.6154	0.2621	0.9659	65
PSCF	O	1285–1360	−4.0814	0.2778	1.1519	87

PSCF	E	1360–1460	−12.0445	0.2180	1.0014	87
PSCF	S	1460–1530	−20.4429	0.1766	0.8743	87
PSCF	C	1530–1565	−26.0624	0.1613	0.8053	87
PSCF	L	1565–1625	−31.5810	0.1666	0.7499	87
PSCF	U	1628–1655	−37.2182	0.1926	0.6988	87
HCF	O	1260–1360	−2.8212	0.0750	2.6053×10^{-4}	310
HCF	E	1360–1460	−3.5158	0.0660	2.0869×10^{-4}	310
HCF	S	1460–1530	−4.1818	0.0595	1.7434×10^{-4}	310
HCF	C	1530–1565	−4.6321	0.0560	1.5679×10^{-4}	310
HCF	L	1565–1625	−5.0754	0.0532	1.4339×10^{-4}	310
HCF	U	1628–1655	−5.5276	0.0506	1.3132×10^{-4}	310

Note: The listed β_2 , α , and γ values are band-averaged model inputs used in the reach-calculation scripts provided in Supplementary Material Code S1. The SMF and PSCF parameters were calculated from the dispersion, attenuation, and nonlinear-coefficient models described in Section 2.1 and Appendix A. The HCF dispersion was estimated using the poor-man's model [14], while the HCF attenuation and nonlinear coefficients were adopted as representative values based on reported HCF loss characteristics and high-speed transmission studies [15,17]. The HCF values therefore represent a reference parameter scenario rather than experimentally verified full-O–U-band data for a single commercially available HCF.

In addition to the intrinsic fiber parameters, amplifier characteristics represent important boundary conditions for link-performance evaluation. A band-specific amplifier configuration was adopted in this study. Erbium-doped fiber amplifiers (EDFAs) were employed for the C and L bands, bismuth-doped fiber amplifiers (BDFAs) for the O and E bands, thulium-doped fiber amplifiers (TDFAs) for the S band, and thulium (Tm)-based amplifiers for the U band. The parameters of the EDFAs for the C and L bands were obtained from commercial device data [18,19]. The parameters of the BDFAs for the O and E bands were derived from the corresponding experimental studies [20,21]. The S-band TDFA parameters were selected with reference to research on broadband S-band amplifiers [22], whereas the U-band amplifier parameters were based on studies of Tm-doped fiber amplifiers [23]. The principal amplifier parameters considered in the model include the operating wavelength range, gain, noise figure (NF), gain flatness, and maximum output power. These parameters directly affect the calculation of amplified spontaneous emission (ASE) noise and the evaluation of link performance. The key performance parameters of the amplifiers used for the different bands are summarized in Table 2.

Table 2. Key performance parameters of optical amplifiers across the modeled O–U-band windows.

Amplifier	Input Wavelength Range (nm)	Gain (dB)	Noise Figure (dB)	Gain Flatness (dB)	Maximum Output Power (dBm)
O-BDFA	1255–1355	19.500–29.250	<5.2	9.0	21.00
E-BDFA	1310–1460	16.250–23.750	4.1–5.7	8.0	23.85
S-TDFA	1458–1524	15.000–23.750	<5.6	8.0	24.84
C-EDFA	1527–1567	17.000–19.000	5.5 (typ.)	1.0 (typ.)	22.00
L-EDFA	1570–1610	20.320–22.200	6.5 (typ.)	1.5 (typ.)	22.00
U-TDFA	1628–1655	4.000–18.700	4.0–10.0	14.0	19.00

Note: The amplifier parameters were compiled from commercial device data and experimental studies reported in [18–23].

To ensure comparability among the different fiber links, a fixed span length was specified for each fiber type according to the principle that the amplifier gain should compensate for the loss of a single span. Based on the attenuation parameters of the fibers in the

different transmission bands and the available amplifier-gain ranges, span lengths of 65 km, 87 km, and 310 km were adopted for SMF, PSCF, and HCF, respectively. The 310 km HCF span should be interpreted as an optimistic reference span derived from the adopted low-loss HCF parameters and amplifier-gain constraints. In practical deployment, connector loss, splice loss, bending-induced loss, mode coupling, and fabrication imperfections may require shorter HCF spans. On this basis, the required amplifier gains for the individual bands were calculated, and the corresponding NFs were determined from the adopted amplifier characteristics, as summarized in Table 3. These values were used as inputs for the subsequent GN-model calculations and auxiliary simulations. This configuration was intended to establish comparable link boundaries under consistent design rules and amplifier constraints, rather than to independently optimize any individual fiber solution.

Table 3. Gain and noise figures of the amplifiers used for SMF, PSCF, and HCF links across the modeled O–U-band windows.

Band	SMF		PSCF		HCF	
	Gain (dB)	Noise Figure (dB)	Gain (dB)	Noise Figure (dB)	Gain (dB)	Noise Figure (dB)
O-low	26.9750	4.7220	N/A	N/A	23.2345	4.7076
O-high	22.5875	4.9230	24.1686	4.9254	—	—
E	19.4220	5.3730	18.9660	5.4378	20.4445	5.4445
S	16.1753	4.6656	15.3599	4.8083	18.4450	4.5716
C	15.0183	5.5000	14.0331	5.5000	17.3600	5.5000
L	15.3745	6.5000	14.4942	6.5000	16.4920	6.5000
U	17.0389	4.5216	16.7573	4.4737	15.6777	4.6215

Note: N/A indicates that the corresponding case was not included in the adopted comparison, whereas—indicates that the entry is not applicable. For HCF, the O band does not require subdivision into O-low and O-high; the listed amplifier parameters are valid for the entire O band.

2.2. Performance Evaluation Method Based on the GN Model

The GN model was employed to provide a unified evaluation of the transmission reach and capacity of different fiber links across the O–U bands. The standard GN model was selected because it provides a computationally efficient framework for comparing multiple fiber types, spectral bands, span configurations, and launch-power conditions under a consistent set of assumptions. Higher-fidelity approaches, such as the enhanced Gaussian noise (EGN) model and split-step Fourier simulations, can provide more detailed nonlinear-interference estimates for specific link designs; however, they require substantially higher computational cost and more detailed system parameters. Therefore, the present GN-model framework is intended for comparative trend analysis and preliminary link screening rather than exact end-to-end system prediction. The GN model is applicable to dispersion-uncompensated links. Under conditions of large accumulated chromatic dispersion, the nonlinear interference (NLI) generated by wavelength-division multiplexing (WDM) signals can be approximated as additive Gaussian noise that is statistically independent of the transmitted signal, thereby enabling system-level comparisons across different fiber types and spectral bands with relatively low computational complexity [9].

Under the GN model, the optical signal-to-noise ratio (OSNR) at the receiver can be expressed as follows

$$\text{OSNR} = \frac{P_{\text{Tx,ch}}}{P_{\text{ASE}} + P_{\text{NLI}}}, \quad (4)$$

where $P_{\text{Tx, ch}}$ denotes the per-channel launch power, P_{ASE} is the amplified spontaneous emission (ASE) noise power, and P_{NLI} is the NLI noise power. ASE noise is mainly determined by the amplifier gain, noise figure, and noise bandwidth. For a single span, the ASE noise power can be calculated as follows

$$P_{\text{ASE, span}} = (G - 1) F h \nu B_n, \quad (5)$$

where G is the linear amplifier gain, F is the noise factor corresponding to the amplifier noise figure on a linear scale, h is the Planck constant, ν is the optical frequency, and B_n is the noise bandwidth. For multiple identical spans, the ASE noise power approximately accumulates linearly with the number of spans N_s . By contrast, the NLI noise power is jointly determined by the fiber dispersion, attenuation, nonlinear coefficient, channel configuration, and launch power, and increases rapidly as the launch power rises. In this study, P_{NLI} was calculated using a closed-form GN-model expression based on the formulation in Ref. [9], with the corresponding MATLAB implementation provided in Supplementary Material Code S1. Consequently, an optimum launch power exists because of the trade-off between ASE noise and NLI noise.

For a given set of fiber parameters, amplifier parameters, and span configurations, the OSNR values under different power conditions were obtained by sweeping the per-channel launch power $P_{\text{Tx, ch}}$. An OSNR threshold of 24 dB at a reference bandwidth of 0.1 nm was adopted as the receiver-side performance criterion [24]. This threshold was used as a common reference criterion to compare different fiber links under consistent assumptions. It should not be interpreted as a universal requirement for all coherent optical systems, because the required OSNR depends on the modulation format, forward-error-correction (FEC) overhead, implementation penalty, target bit-error rate, and transceiver design. The possible influence of alternative OSNR thresholds is therefore discussed in the revised analysis. At each launch-power point, the maximum feasible number of spans N_s satisfying this criterion was determined. The corresponding total transmission reach was then calculated as follows

$$L_{\text{total}} = N_s L_s, \quad (6)$$

where L_{total} is the total transmission reach and L_s is the span length. Based on the resulting $L_{\text{total}}(P_{\text{Tx, ch}})$ curves, the optimum launch power $P_{\text{Tx, opt}}$ and maximum transmission reach of each band-specific link were extracted. $P_{\text{Tx, opt}}$ corresponds to the operating point at which ASE noise and NLI noise are optimally balanced, and provides the basis for the subsequent comparisons of transmission reach and capacity.

For the capacity evaluation, the OSNR was first converted into the signal-to-noise ratio (SNR) using the OSNR reference bandwidth, as follows

$$\text{SNR} = \text{OSNR} \times \frac{B_0}{R_s}, \quad (7)$$

where B_0 is the OSNR reference bandwidth and R_s is the symbol rate. In the calculations, $R_s = 64$ Gbaud, and B_0 was obtained by converting the OSNR reference bandwidth of 0.1 nm into the corresponding frequency bandwidth at the representative wavelength of each band or sub-band. For the SMF O-low and O-high sub-bands, a common reference wavelength of 1310 nm was adopted solely for this conversion to maintain a consistent O-band OSNR reference. In Equation (7), OSNR and SNR are expressed in linear units. The per-channel capacity C_{ch} was subsequently calculated using the Shannon–Hartley theorem:

$$C_{\text{ch}} = R_s \log_2 (1 + \text{SNR}). \quad (8)$$

The total capacity of the corresponding band was calculated as follows

$$C_{\text{band}} = N_{\text{ch}} C_{\text{ch}}, \quad (9)$$

where N_{ch} is the number of channels accommodated within the corresponding band. The resulting values represent theoretical capacity estimates under the adopted modeling assumptions. Because the Shannon–Hartley theorem provides an upper-bound capacity estimate, the practical net throughput of coherent systems would be lower when modulation-format constraints, FEC overhead, coding gaps, implementation penalties, transceiver noise, DSP limitations, and nonlinear system penalties are included. Therefore, the capacity values reported in this work are used as comparative theoretical indicators rather than direct predictions of deployable net capacity. To establish a consistent non-saturated reference condition, equal-coverage calibration was applied to the reach–power curves within each fiber type. For each fiber type, a feasible common reference reach was selected for the included bands, and the corresponding band-specific per-channel launch powers were extracted from the $L_{\text{total}}(P_{\text{Tx,ch}})$ curves. These operating points were then used to calculate the per-channel capacity and total capacity per band. Because the achievable reach ranges differ substantially among the three fiber types, the resulting capacities are intended for comparative trend evaluation rather than as a strict same-distance end-to-end benchmark across fiber types.

In addition to the baseline comparison, a supplementary scenario in which the amplifiers operate at their saturated-output powers was considered to evaluate the potential capacity boundaries of the different links under higher power budgets. It should be noted that the saturated-output condition is primarily intended to characterize the upper capacity limit and does not represent the optimum power allocation in a practical system. In ultra-wideband transmission systems, launch-power optimization continues to have a significant influence on the overall system throughput [25].

In summary, the performance evaluation procedure adopted in this study is as follows. First, the D , α , and γ parameters of the three fiber types across the O–U bands, together with the corresponding band-specific amplifier parameters, were used as model inputs. Second, the OSNR and L_{total} values under different launch-power conditions were calculated using the GN model, from which the optimum launch power and maximum transmission reach were extracted. Finally, the capacity was evaluated using within-fiber equal-coverage calibration under consistent amplifier constraints, and the theoretical trends were further examined through auxiliary VPIphotonics simulations. This procedure provides a unified basis for the comparative evaluation of different fiber links across the O–U bands. The resulting reach and capacity values should therefore be understood as model-based comparative indicators under the adopted parameter assumptions.

To examine the consistency of the overall trends obtained from the GN-model calculations, simplified link models for representative C-band cases were established using VPIphotonics Design Suite version 11.1, with input parameters consistent with those adopted in the theoretical analysis, including the span lengths, amplifier gains, and noise figures. The auxiliary simulations were restricted to representative C-band cases and were used to check the consistency of the main reach–power trends, including the variation in OSNR with per-channel launch power and span count. They were not intended to replace full split-step Fourier simulations or experimental validation across the entire O–U range, nor to serve as an independent set of performance-optimization results.

3. Performance Evaluation Results

3.1. Comparison of Maximum Transmission Reach

Based on the parameter settings and model established in Section 2, including the band-specific fiber and amplifier parameters summarized in Tables 1–3, the relationship between the total transmission reach L_{total} and the per-channel launch power $P_{\text{Tx,ch}}$ was first calculated for the three fiber types across the O–U bands. The maximum transmission reach of each band was then extracted accordingly. For each band, the peak of the

$L_{\text{total}}(P_{\text{Tx,ch}})$ curve corresponds to the maximum transmission reach $L_{\text{total,max}}$. The reach–power curves of the three fiber types across the O–U bands are shown in Figure 1, where panels (a)–(c) present the calculation results for SMF, PSCF, and HCF, respectively.

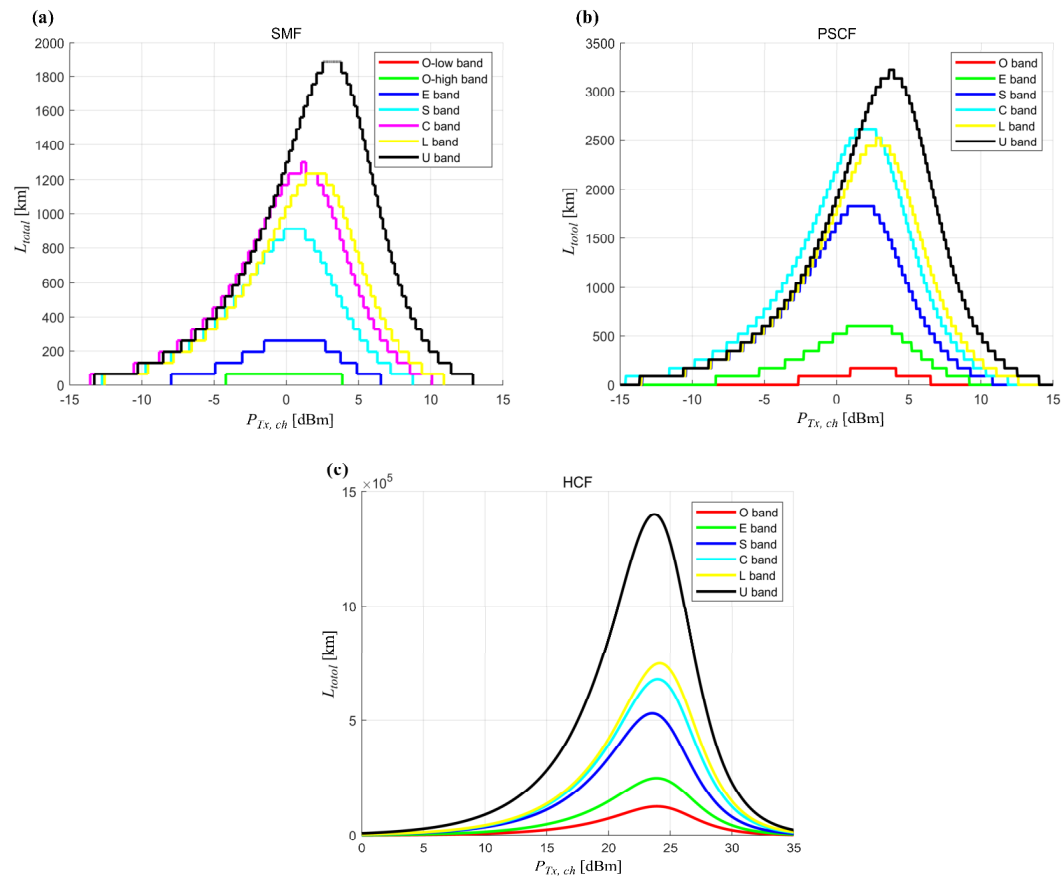


Figure 1. Transmission reach L_{total} versus per-channel launch power $P_{\text{Tx,ch}}$ calculated using the GN model for the three fiber types across the O–U bands: (a) standard single-mode fiber (SMF); (b) pure-silica-core fiber (PSCF); and (c) hollow-core fiber (HCF).

Regarding the band dependence, the U band generally exhibits the largest $L_{\text{total,max}}$ under the adopted parameter settings, whereas the relative ordering of the remaining bands varies with the adopted fiber and amplifier parameters. This indicates that, under the parameter settings adopted in this study, the combined effects of dispersion, reduced nonlinear coefficients at longer wavelengths, and band-dependent amplifier characteristics contribute to suppressing NLI accumulation, thereby extending the achievable transmission reach. However, the maximum transmission reach is also affected by band-dependent attenuation, amplifier noise figure, and gain range. Therefore, the differences among the spectral bands cannot be fully explained by any single fiber parameter. These results should therefore be interpreted as the combined outcome of fiber loss, dispersion, nonlinear coefficient, span length, and amplifier noise characteristics rather than as a consequence of fiber properties alone.

The comparison among the different fiber types shows that PSCF and SMF exhibit broadly consistent band-dependent trends. However, the maximum transmission reach of PSCF is generally greater than that of SMF in the principal operating bands, indicating that its larger effective mode area and relatively favorable loss characteristics contribute to improved long-haul transmission performance. In HCF, the optical field is predominantly distributed within the air core, resulting in substantially reduced Kerr nonlinearity. Consequently, the GN-model calculations predict higher power tolerance and a longer

theoretical transmission reach for HCF under the adopted representative HCF parameter scenario. These results indicate that the advantages of PSCF primarily arise from the balance between low loss and low nonlinearity in a solid-core structure, whereas those of HCF are more directly attributable to its extremely low nonlinearity. It should be emphasized that the HCF reach values are theoretical predictions under the adopted simplified loss and nonlinearity assumptions and should not be interpreted as directly achievable end-to-end transmission distances. In practical HCF links, additional connector loss, splice loss, bending-induced loss, mode coupling, and fabrication-related imperfections may reduce the achievable reach.

In addition, the reach–power curves of SMF and PSCF exhibit relatively pronounced step-like features. This is because the achievable number of spans N_s is restricted to integer values. By contrast, HCF has a longer span length and a substantially longer predicted transmission reach. As a result, the step-like variations are less apparent over the plotting range used in this study than those observed for the solid-core fibers. This difference in curve appearance is therefore partly a consequence of the adopted span-length discretization and should not be overinterpreted as an independent physical advantage of HCF.

3.2. Comparison of Optimum Launch Power

After obtaining the $L_{\text{total}}(P_{\text{Tx,ch}})$ curves, the optimum launch power $P_{\text{Tx,opt}}$ corresponding to the peak of each curve was extracted. This parameter reflects the operating condition at which ASE noise and NLI are relatively balanced within the link. When $P_{\text{Tx,ch}}$ is relatively low, the system is primarily limited by ASE noise, and increasing the launch power contributes to improving the OSNR. When $P_{\text{Tx,ch}}$ continues to increase beyond $P_{\text{Tx,opt}}$, NLI accumulates rapidly, resulting in a decrease in transmission reach.

As shown in Figure 1, $P_{\text{Tx,opt}}$ varies considerably among the different spectral bands. Overall, the longer-wavelength bands correspond to higher optimum launch powers, with the U band generally exhibiting the highest $P_{\text{Tx,opt}}$. This indicates that, at longer wavelengths, weaker nonlinear effects enable the link to tolerate a higher per-channel launch power without prematurely entering the nonlinearity-limited regime. Nevertheless, this trend is also influenced by the band-dependent attenuation and amplifier noise figures adopted in the model.

Regarding the different fiber types, SMF and PSCF exhibit similar trends in the distribution of $P_{\text{Tx,opt}}$. However, PSCF generally permits a higher optimum launch power in the principal operating bands. The $P_{\text{Tx,opt}}$ values of HCF are distinctly shifted toward higher power levels, indicating that its air-guiding structure substantially reduces nonlinear accumulation and enables the link to maintain favorable OSNR performance at higher launch powers. This result should be understood as a theoretical power-tolerance trend under the representative HCF parameters used in this study. In practical systems, amplifier output limits, transceiver constraints, fiber handling, splice/connector losses, and safety or damage thresholds may further constrain the usable launch power. Therefore, the comparison of optimum launch power further demonstrates the differences in power tolerance among the different fiber types and provides a basis for the subsequent capacity analysis.

3.3. Capacity Comparison

After obtaining the maximum transmission reach and optimum launch power for each spectral band, the capacity characteristics of the different fiber links were further evaluated under calibrated non-saturated operating conditions. For each fiber type, equal-coverage calibration was applied to the included bands, and the corresponding band-specific per-channel launch powers were extracted from the reach–power curves. The per-

channel capacity was then calculated, and the total capacity per band was obtained by multiplying the per-channel capacity by the number of channels determined from the available bandwidth of that band. As described in Section 2.2, these capacity values are Shannon–Hartley-based theoretical estimates and are used here as comparative indicators rather than as practical net-throughput predictions. The capacity comparisons under non-saturated and saturated-output conditions are shown in Figure 2a–d. Panels (a) and (b) present the per-channel capacity and total capacity per band under non-saturated conditions, respectively, whereas panels (c) and (d) show the corresponding upper capacity limits when the amplifiers operate at their maximum output powers. The numerical source data underlying Figure 2 are provided in Supplementary Material Data S1.

Under the adopted non-saturated reference operating conditions, the capacity comparison for SMF and PSCF primarily covers the S, C, L, and U bands. The O and E bands of SMF and PSCF were excluded because their achievable transmission reaches differ substantially from those of the other bands. This exclusion was applied only to the unified capacity comparison in order to avoid mixing bands with markedly different feasible reference reaches; it does not imply that the O and E bands are intrinsically unsuitable or unimportant for all SMF and PSCF transmission scenarios. For SMF, the C band exhibits the highest per-channel capacity, whereas the S, L, and U bands show comparable values. PSCF exhibits a capacity distribution trend similar to that of SMF, with the C band likewise showing a relatively high per-channel capacity. By contrast, the per-channel capacities of HCF in the S, C, L, and U bands are consistently higher than those of SMF and PSCF, with the U band exhibiting the best performance. At the selected non-saturated reference operating points, the per-channel capacities of HCF in the S, C, L, and U bands are approximately 38.3%, 34.5%, 42.6%, and 54.4% higher than those of SMF, respectively. Compared with PSCF, the corresponding improvements are approximately 38.3%, 33.2%, 42.4%, and 59.7%, respectively. These percentage improvements are model-based results obtained under the adopted fiber and amplifier parameters, and they should not be interpreted as uncertainty-free experimental performance margins.

Regarding the total capacity per band, the combined effects of the channel count and available bandwidth further enhance the advantage of HCF. HCF not only exhibits higher per-channel capacities in the S, C, L, and U bands, but also provides effective capacity contributions in the O and E bands within the adopted HCF parameter scenario. Consequently, the total capacities per band of HCF are substantially higher than those of SMF and PSCF in the present theoretical comparison. Under saturated-output conditions, the capacities of most bands increase further. The improvements are more pronounced in the L and U bands, whereas the increase in the C band is relatively limited. It should be noted that the saturated-output condition is primarily used to characterize the upper capacity limit and does not represent the optimum power-allocation scheme in a practical system. In practical coherent systems, modulation-format constraints, FEC overhead, transceiver noise, DSP limitations, and implementation penalties would reduce the achievable net capacity relative to the Shannon-based estimates reported here.

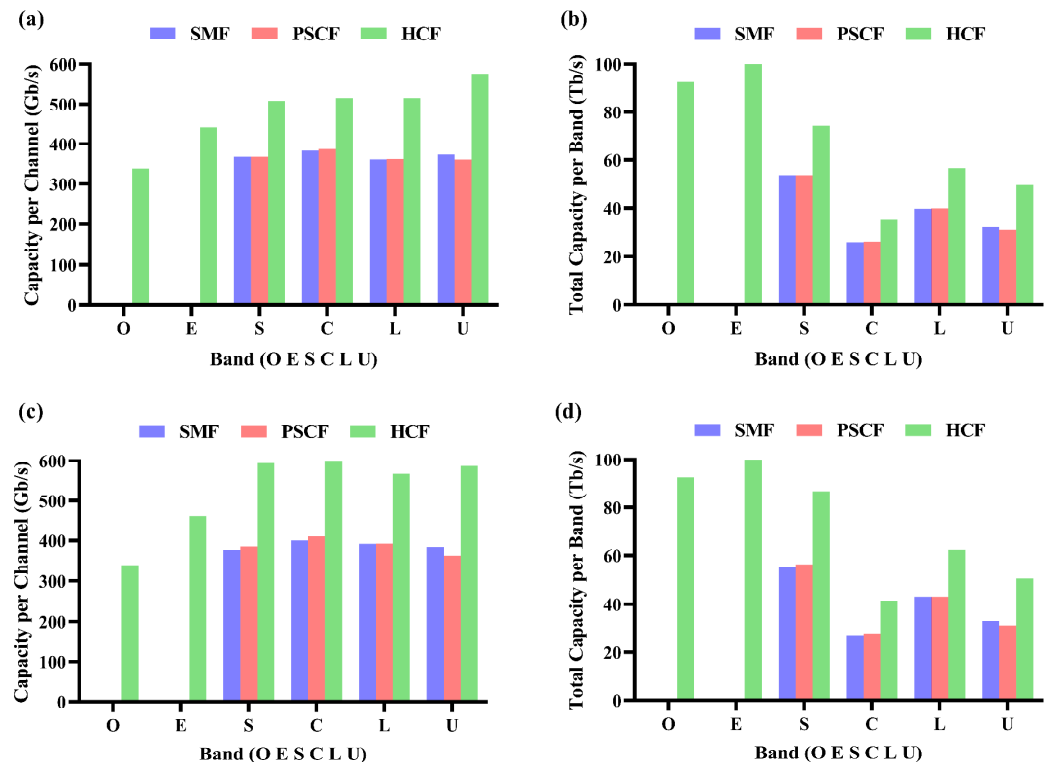


Figure 2. Comparison of the theoretical per-channel capacities and total capacities per band of the three fiber types across the O–U bands. The bands are arranged in the order O, E, S, C, L, and U. For SMF and PSCF, the O and E bands are excluded from the unified capacity comparison because their achievable reaches differ substantially from those of the other bands. (a) Per-channel capacity under the adopted non-saturated reference operating conditions; (b) total capacity per band under the corresponding non-saturated conditions; (c) upper limit of the per-channel capacity when the amplifiers operate at their maximum output powers; and (d) total capacity per band under saturated-output conditions.

4. Discussion

The results presented in Section 3 indicate that the performance differences among the fiber links across the O–U bands are not determined by any single parameter, but arise from the combined effects of chromatic dispersion, attenuation, nonlinear coefficient, and amplifier characteristics. In terms of transmission reach, the improvement of PSCF over SMF primarily reflects the combined advantages of low attenuation and relatively low nonlinearity. By contrast, the model-predicted performance potential of HCF is more directly attributable to the extremely low Kerr nonlinearity enabled by its air-guiding structure. Therefore, under the adopted parameter settings and amplifier constraints, the low-loss solid-core solution and the low-nonlinearity hollow-core solution represent two distinct routes for improving transmission performance within the theoretical comparison framework used in this study.

The variation in optimum launch power further illustrates the trade-off between ASE noise and NLI. The lower nonlinear coefficient of PSCF enables it to tolerate higher launch powers than SMF. The optimum launch power of HCF is distinctly shifted toward higher power levels, indicating that its low-nonlinearity structure expands the usable launch-power range of the link under the representative HCF parameters adopted here. The capacity comparison is also consistent with this trend. At the selected non-saturated reference operating points, HCF can achieve a higher effective SNR and therefore exhibits more pronounced theoretical advantages in terms of per-channel capacity and total capacity per band. It should be noted that the saturated-output condition is primarily used to charac-

terize the upper capacity limit and does not represent the optimum power-allocation scheme in a practical system.

The influence of individual parameters can be interpreted from the GN-model formulation. Fiber attenuation and amplifier noise figure mainly determine ASE accumulation and therefore strongly affect the maximum transmission reach. The nonlinear coefficient directly controls the strength of NLI and hence has a major influence on the optimum launch power and nonlinear power tolerance. Chromatic dispersion affects NLI accumulation, while amplifier gain and span length jointly determine span-loss compensation and ASE contribution. Therefore, the reported reach and capacity trends should be understood as the combined result of these parameters rather than as being determined by one fiber property alone.

The HCF results require particular caution. The HCF parameters used in this study represent a model-based reference scenario rather than experimentally verified full-O-U-band data for a single commercially available HCF. In practical HCF deployment, connector loss, splice loss, bending-induced loss, mode coupling, fabrication imperfections, and environmental effects may reduce the achievable reach and capacity. Recent studies have demonstrated improved bending resistance and temperature-insensitive operation in specific HCF designs [7,8], but full-system validation over the complete O-U range is still required. Accordingly, the HCF results in this work should be interpreted as indicating potential performance advantages under the adopted low-loss and low-nonlinearity assumptions, rather than as direct evidence of immediately achievable full-O-U-band deployment performance.

From a modeling perspective, the primary role of the GN model in this study is to provide a unified basis for comparing different fiber links. The overall trends observed in the representative C-band auxiliary simulations are consistent with the GN-model predictions, indicating that the model can capture the principal physical trends in comparisons of transmission reach and capacity. However, the GN model adopts an approximate treatment of nonlinear interference. Its results are therefore more suitable for trend analysis and relative comparisons than for direct interpretation as absolute performance values in complex engineering links. Higher-fidelity approaches, such as enhanced GN-model formulations, split-step Fourier simulations, and experimental O-U-band transmission measurements, are still required for more accurate system-level prediction and engineering design.

5. Conclusions

To address the difficulty of directly comparing the performance of different fiber types in ultra-wideband links spanning the O-U bands, a GN-model-based framework for link-performance analysis was established. The transmission reach, optimum launch power, and theoretical capacity characteristics of SMF, PSCF, and HCF across the O-U bands were subsequently compared. The results show that the three fiber types exhibit distinct performance characteristics across the O-U bands. PSCF generally outperforms SMF in terms of transmission reach, whereas HCF demonstrates greater theoretical capacity potential under the adopted representative parameter assumptions owing to its substantially lower nonlinear coefficient.

The results indicate that no single fiber solution is universally optimal across the O-U bands. Instead, the fiber type should be selected according to the link-design objective. For applications prioritizing long-haul transmission within solid-core fiber systems, PSCF is a more competitive candidate. For applications prioritizing high-capacity transmission, HCF may offer considerable potential if low-loss, low-nonlinearity, and practically deployable HCF links can be realized across the relevant wavelength bands. The representative C-band auxiliary simulations showed overall trend consistency with the theoretical

analysis, supporting the use of the GN model for rapid performance comparison and preliminary selection among different fiber links.

Overall, rather than attempting to provide a comprehensive investigation of ultra-wideband links, this study aims to offer a clear and practical analytical approach for comparing the performance of different fiber links across the O–U bands. The reported HCF reach and capacity values should not be interpreted as absolute deployment limits, because practical performance may be affected by parameter uncertainty, splice/connector loss, bending sensitivity, mode coupling, fabrication imperfections, amplifier constraints, and transceiver implementation penalties. Further refinement using higher-fidelity numerical simulations and experimental results is still required for more detailed engineering design and performance evaluation.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/photonics13070647/s1>: Code S1: MATLAB scripts and an accompanying README file for wavelength-dependent fiber-parameter calculations and GN-model-based reach–power curves; Data S1: Numerical source data underlying the capacity comparisons shown in Figure 2.

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Abbreviations

The following abbreviations are used in this manuscript:

ASE	Amplified spontaneous emission
BDFA	Bismuth-doped fiber amplifier
EDFA	Erbium-doped fiber amplifier
GN	Gaussian noise
HCF	Hollow-core fiber
NF	Noise figure
NLI	Nonlinear interference
OSNR	Optical signal-to-noise ratio
PSCF	Pure-silica-core fiber

SMF	Standard single-mode fiber
SNR	Signal-to-noise ratio
TDFA	Thulium-doped fiber amplifier
WDM	Wavelength-division multiplexing

Appendix A. Selected Fiber-Model Input Parameters

The selected model coefficients used to generate the band-averaged fiber parameters in Table 1 are summarized in Table A1. For the attenuation fitting coefficients, the wavelength was expressed in meters for SMF and in micrometers for PSCF. The HCF attenuation and nonlinear parameters were assigned based on Refs. [15] and [17], respectively.

Table A1. Selected fiber-model input parameters used in the calculations.

Fiber	Parameter	Value	Unit	Source
SMF	Dispersion fitting coefficient p_1	150.5	μm^{-3}	[11]
SMF	Dispersion fitting coefficient p_2	−549.6	μm^{-2}	[11]
SMF	Dispersion fitting coefficient p_3	918.8	μm^{-1}	[11]
SMF	Dispersion fitting coefficient p_4	−600.0	—	[11]
SMF	Dispersion fitting coefficient q_1	1.374	μm^{-1}	[11]
SMF	Dispersion fitting coefficient q_2	−0.4602	—	[11]
SMF	Attenuation fitting coefficient A	8.5×10^{-25}	$\text{dB}\cdot\text{m}^4/\text{km}$	Fitted following [26]
SMF	Attenuation fitting coefficient B	0.024	dB/km	Fitted following [26]
SMF	Attenuation fitting coefficient C	4.6×10^{-14}	dB/km	Fitted following [26]
SMF	Attenuation fitting coefficient D	1.72×10^7	m^{-1}	Fitted following [26]
SMF	UV-loss coefficient E_{UV}	2.0789×10^{-7}	$\text{dB}\cdot\text{m}/\text{km}$	Fitted following [26]
SMF	UV-loss width parameter w_{UV}	3.0892×10^{-7}	m	Fitted following [26]
SMF	UV-loss center wavelength $\lambda_{c,UV}$	6.0001×10^{-7}	m	Fitted following [26]
SMF	Effective mode area (A_{eff}) at 1550 nm	80	μm^2	Model input used in this study
SMF	Nonlinear refractive index (n_2) at 1550 nm	2.28×10^{-20}	m^2/W	Model input used in this study
PSCF	Mode-field diameter $2w$ at 1310 nm	10.8	μm	[13]
PSCF	Mode-field diameter $2w$ at 1550 nm	11.9	μm	[13]
PSCF	Nonlinear refractive index n_2 at 1550 nm	2.2×10^{-20}	m^2/W	Model input used in this study
PSCF	Rayleigh-scattering coefficient A	8.4×10^{-25}	$\text{dB}\cdot\text{m}^4/\text{km}$	Fitted following [27]
PSCF	Attenuation fitting coefficient C	3250	dB/km	Fitted following [27]
PSCF	Attenuation fitting coefficient c	20	μm	Fitted following [27]
PSCF	Attenuation fitting coefficient D	7.93×10^{14}	dB/km	Fitted following [27]
PSCF	Attenuation fitting coefficient d	61	μm	Fitted following [27]
HCF	First zero of the zeroth-order Bessel function u_{01}	2.405	—	Used in the poor-man's model [14]
HCF	Effective core radius R_{eff}	14.4	μm	Model input used in this study; poor-man's model based on [14]
HCF	Effective mode area (A_{eff}) at 1550 nm	572	μm^2	Model input used in this study
HCF	Nonlinear refractive index n_2	2.2×10^{-23}	m^2/W	Adopted model input based on [17]

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