Multi-Core vs Hollow-Core Fibers: Technical Study of their Viability in SDM Power-Constraint Submarine Systems

A. Carbo Meseguer [(1)], J. L. de O. Pacheco [(1)], J.C. Antona [(1)], J.T. de Araujo [(1)] and V. Letellier [(1)]

[(1)] Alcatel Submarine Networks, Nokia Paris-Saclay 91620 Nozay (France), alexis.carbo_meseguer@asn.com

Abstract *We study the viability of Multi-core and Hollow-core fibers for submarine links, considering transceiver limitations and typical power constraints of SDM systems. We discuss the challenges that these technologies will face to be adopted in the long term. ©2022 The Author(s)*

Introduction

The growth in the capacity demand has been significant in the last decades and its upward trend is still firm [1]. The development of new disruptive technologies is necessary to meet future demands. Spatial Division Multiplexing (SDM) is the latest technology adopted by the submarine community to cope with this increase of capacity demand. So far, this technology is mainly based in the transmission of several fibers in parallel and the use of pump farming to feed optical repeaters [2-3]. Current fiber technology is single-core pure-silica core fiber (SC-PSCF) that was adopted in the early 1980s and its attenuation has been improved over time reaching values of 0.142 dB/km [4]. With each attenuation improvement, different underwater transmission records have been achieved. Nowadays, it seems more and more challenging to produce capacity increases by only improving the proprieties of this fiber, so a new technology should be exploited. There seems to be two possible candidates:

On the one hand, the multi-core fiber (MCF) has attracted the optical community attention and technical-economic studies have already been performed to show the advantages of uncoupled core (UC) 2 and 4 core MCF for submarine systems [5], even first transmission experiments are done using cabled MCF [6]. In longer term, Coupled Core (CC) technologies could further increase core density if multi-core MIMO processing is implemented at receivers [7].

On the other hand, a recent development of a new type of Hollow-core fiber (HCF) based on Nested Antiresonant Nodeless Fiber (NANF) [8] has recently become popular since the demonstration of attenuations close to the record of PSCF (0.174 dB/km [9]), and potentially get even lower ones (<0.1 dB/km is discussed in [10]). Furthermore, this optical fiber would have very good transmission proprieties such as increased transmission bandwidth and extremely low nonlinearities, thus enabling higher powers.

The debate is now opened to figure out which is the most promising technology, more specifically in submarine systems where fiber attenuation and nonlinearities have always been key parameters for transmission records. Some promising studies have already been published with very significant gains for HCF with respect conventional PSCF systems [10]. However, it is shown in [11] that this potential could be partially hidden by the transceiver noise.

But another constraint exists in submarine systems: since the rise of SDM, the number of FP per cable has increased in order to maximize the cable capacity and high FP count up to 24 is announced [12]. With this trend, total transmitted power per band is likely to be reduced due to energy constraints. It seems then challenging to operate the HCF in the regime where it could show its real potential.

This work numerically assesses the performance of UC 2-4 core MCF over C band (5 THz bandwidth) and a Hollow-core C+L (11 THz), exploiting power limitations from the Power Feeding Equipment (PFE). Finally, a longer-term scenario is studied with coupled-core 7-core MCFs, C+L in MCF systems, and HCFs with 35-45 THz max bandwidth following trends in [8-10].

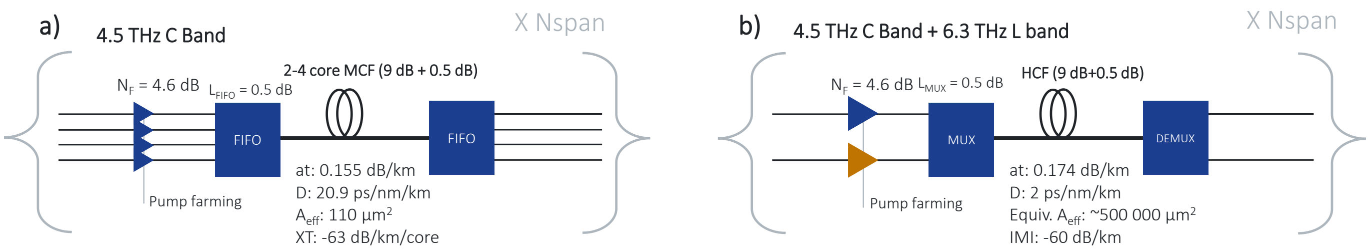

Fig. 1: Test beds considered in this study: (a) the multi-core (MCF) and (b) the Hollow-core fiber (HCF).

Transmission setups

Multi-core fiber test bed

The MCF transmission system is shown in Fig.1a. An UC 2-4 core MCF is first studied. This fiber has 0.155 dB/km attenuation, 20.9 ps/nm/km chromatic dispersion and nonlinear coefficient γ_{NL}=0.95 W^{-1} km^{-1} which represents an effective area around 110 μm^2. Crosstalk between cores is fixed at –63 dB/km/core. Transmission is performed in 5-THz band. Span length is adapted to have an optimal loss of 9 dB (~60 km) as in [13] and an additional loss of 0.5 dB is also considered. Single-core Erbium-Doped Fiber Amplification (EDFA) is used to recover transmitting power with a noise figure of 4.6 dB. Some fan-in fan-out (FIFO) are required to multiplex/demultiplex signals in the MCF with 2 x 0.5dB insertion loss.

Hollow-Core Fiber test bed

On the other hand, Fig.1b depicts the HCF setup. Attenuation is varied from the lowest value ever reported at the time of submission of this publication (0.174 dB/km in [9]) to a potential value of 0.05 dB/km. Span length is also adapted to obtain span loss around 9 dB [13]. For instance, for 0.174 dB/km the length is ~50 km. Chromatic dispersion is 2 ps/nm/km and γ_{NL}= 2e10^{-4} W^{-1} km^{-1}, representing an equivalent effective area of ~500 000 μm^2. We also considered an Intermodal Interference (IMI) equal to –60 dB/km. These parameters are in the same order of magnitude than previous simulations performed in [10-11]. Transmission is performed in C+L (~11 THz bandwidth). In this case, multiplexers/demultiplexers are considered with an insertion loss of 2x0.5 dB. Single band EDFAs are used to recover launching power with 4.6 dB of noise figure.

For both systems, submarine cables up to 48 FP are considered. 98 GBd signals are transmitted with 100-GHz channel spacing. Number of spans is adapted to the simulated to distance of 6000 km and 12000 km.

Electric and optic model of the EDFA for pump farming SDM submarine systems

For the optical transmission, a Gaussian Noise (GN) model [14] simulates the impact of fiber nonlinearities. For MCF systems, penalty from Guided Acoustic Wave Brillouin Scattering (GAWBS) noise is also considered [15], but not for HCF since it is assumed to be negligible due to the larger effective area of the fiber. In order to aggregate impairments, the droop model is used [16]. The total achievable capacity is predicted with the adapted Shannon formula (SNR_{tx}=19 dB and a Γ = 3 dB) [17].

Since we study these systems in an SDM environment, with many fiber pairs (FP) in parallel and pump farming, we must consider that they can be potentially power constrained, and an electric model must be studied. A net available power for repeaters P_{net} is considered as the PFE max power P_{max} minus cable loss: $P_{net} = P_{max} – I^2 * R_{cable} – P_{extra\text{-}loss}$. Here I is the injected current in the cable, R_{cable}, the conductor resistivity and $P_{extra\text{-}loss}$ is an additional loss or margin, for instance Magnetic Storm Allowance (MSA). The number of pumps per repeater is obtained from the number of spans N_{spans} and required voltage per pump V_{pump}: $N_{pumps} = P_{net} / (I * N_{spans} * V_{pump})$. V_{pump} in our study we took 2,85 V (30% of which are dedicated to circuiting and control [18]). Finally, once the N_{pumps} is known, the total output power (TOP) is estimated following a well-tuned affine law as a function of the power per pump as explained in [19-20].

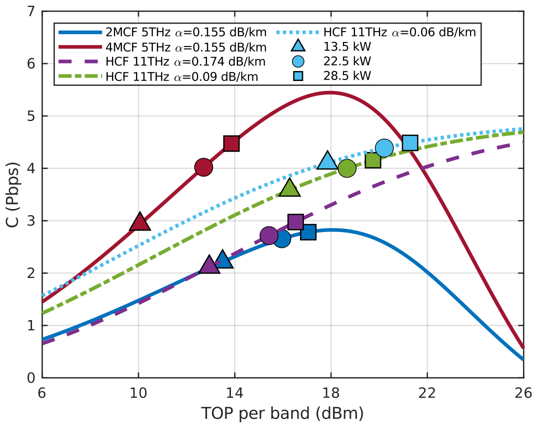

Fig. 2: HCF C+L system compared with MCF 2-4 core (C band) as a function of total output power per equivalent bands of 5 THz.

Mid-term scenario: 2-4 core MCF (C band) and HCF 11 THz (C+L band)

Fig. 2 shows the predicted capacity of a submarine cable with exactly 48 FP after a 6000 km transmission as a function of the total input power (TOP) per band for 2 and 4 cores MCF (C band) and the HCF (C+L band). A nonlinear threshold (NLT) is observed for MCF around 18 dBm. In HCF, the NLT is not visible and capacity is saturating at high TOP due to SNR_{tx} as reported in [11].

In SDM systems with high FP count, it is not possible to operate the system at powers around or beyond the NLT. To illustrate it, the maximum TOP that can achieved is shown in Fig. 2 for P_{net} values equal to 13.5, 22.5 and 28.5 kW (markers) for 48 FP. With these values we observe that the delivered capacity by current HCF technology is comparable only to 2-core MCF and not with 4-core MCF since this last fiber has a doubled equivalent bandwidth.

It must be noticed though that HCF has more potential for loss reduction than PSCF [8]. This feature can be exploited to approach the performance of 4-core MCF due to the reduction in the number of repeaters when constant span loss is considered, as suggested by [13]. Fig. 2 shows the predicted capacity when the HCF attenuation is reduced to future potential of 0.09 and 0.06 dB/km values. We observe that now HCF could have a similar performance as the 4-core MCF at the same P_{net}. For instance, to reach 4 Pbps, a 4-core MCF would be comparable to a HCF with 0.09 dB/km with a P_{net} of ~22.5 kW (circles) and, if the target is 4.5 Pbps, with a HCF with 0.06 dB/km and a P_{net} of ~28.5 kW (squares). It is then impossible to keep growing in capacity since HCF finally saturates to SNR_{tx}.

Long-term scenario: 7-core MCF (C+L) and HCF up to 45 THz

Finally, a last assessment is done to study long term scenarios with up to 48 FP. MCFs with 0.13 dB/km attenuation are considered. We also included a CC 7-core MCF over C+L band. On the other hand, 15-35-45 THz total optical bandwidth HCFs are studied with 0.1 dB/km attenuation, and even a potential 0.05 dB/km. It is indeed the final potential features that HCF can obtain according to [8]. How these very wide bands are amplified is outside the scope of this work, however an extra loss of 1-3-5 dB respectively in SNR_{ASE} is considered to account for the associated potential amplification reduced efficiency as is shown in [21]. Total predicted capacity at 6000 km and 12000 km is represented in Fig. 3 as a function of P_{net}. (As a reference, if I=1A and R_{cable}=1Ω/km, for a P_{max}=18 kV, we would have a P_{net} of 12 kW for 6000 km and 6 kW for 12000 km). At 6000 km, we observe that 4-core MCF (C band) would be comparable to HCF 0.1 dB/km 15 THz (S+C+L). On the other hand, 4-core MCF (C+L) or 7-core MCF (C) would enable higher capacity and it would lead to similar values than 15 THz HCF with 0.05 dB/km. If more futuristic scenarios are allowed and transmission bandwidth could be extended up to 35 THz, HCF with 0.1 dB/km would also deliver similar capacities than previous cases. 35-45 THz HCF with 0.05 dB/km would significantly increase the achievable capacity with respect to MCF and the only one that could follow would be 7-core (C+L) at very high P_{net} values. Similar analysis can be done at 12000 km where the potential of HCF is even clearer since MCF scenarios are extremely constrained by power limitations and HCF is less penalized due to span number reduction.

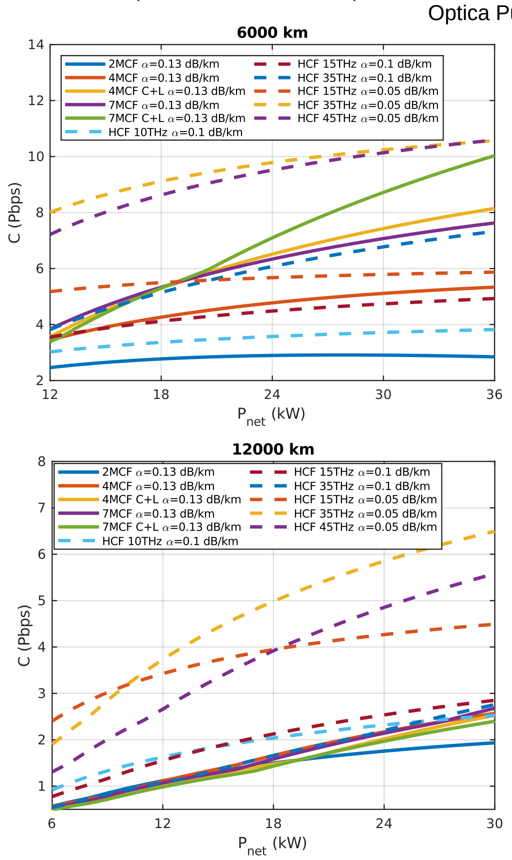

Fig. 3: Capacity prediction for different long-term scenarios at 6000 and 12000 km versus net system powering.

Conclusion

In this study, two future fiber candidates are evaluated. On the one hand the MCF, that has recently attracted the attention of the submarine community and on the other hand a recently arrived NANF Hollow-core fiber. We have performed a numerical assessment in a <48 FP submarine environment in order to experience power limitations, and we show that with realistic amplification schemes based on EDFA, HCF is not competitive yet against the 4-core MCF since its optical bandwidth is limited to ~11 THz. However, this study further shows that this issue can be partially solved if HCF attenuation is reduced to potential values down to 0.05 dB/km, but it is not enough because SNR_{Tx} limits the achievable capacity of the system. Nevertheless, if an amplification technology could be developed to benefit from the total potential bandwidth up to 35-45 THz of the HCF, then this fiber would be with no doubt the one that could enable submarine cables up to 10 Pbps and 5 Pbps for transatlantic and transoceanic distances respectively, but still in a very long-term scenario.

References

[1] P. Winzer, "Capacity Scaling Through Spatial Parallelism: From Subsea Cables to Short-reach Optical Links, " in Optical Fiber Communications Conference and Exhibition (OFC), 2021, pp. 1-3.

[2] M. Bolshtyansky et al., “Cost-optimized single mode SDM Submarine Systems,” in Suboptic Conference, 2019, pp. 1-3

[3] P.Pecci et al., “Pump farming as enabling factor to increase subsea cable capacity,” in Suboptic Conference, 2019, pp. 1-3

[4] Y. Tamura, "Ultra-low Loss Silica Core Fiber," in Optical Fiber Communications Conference and Exhibition (OFC), 2018, pp. 1-3.

[5] J. D. Downie, Xiaojun Liang, and Sergejs Makovejs, "Modeling the Techno-Economics of Multicore Optical Fibers in Subsea Transmission Systems," in J. Lightwave Technol. 40, 1569-1578 (2022)

[6] H. Takeshita, K. Nakamura et al., "First Demonstration of Uncoupled 4-Core Multicore Fiber in a Submarine Cable Prototype with Integrated Multicore EDFA," in Optical Fiber Communications Conference and Exhibition (OFC), 2022, pp. 1-3.

[7] M. Mazur et al., "Real-Time Transmission over 2×55 km All 7-Core Coupled-Core Multi-Core Fiber Link," in Optical Fiber Communications Conference and Exhibition (OFC), 2022, pp. 1-3.

[8] F. Poletti, “Nested Antiresonant Nodeless Hollow-Core Fiber,” Opt. Express, vol. 22, pp. 23807–23828, 2014.

[9] G. T. Jasion et al., “0.174 dB/km Hollow Core Double Nested Antiresonant Nodeless Fiber (DNANF),” in Optical Fiber Communications Conference and Exhibition (OFC), 2022, pp. 1-3.

[10] P. Poggiolini and F. Poletti, “Opportunities and Challenges for Long-Distance Transmission in Hollow-Core Fibres,” in J. Lightwave Technol. 40, 1605-1616 (2022).

[11] W. Klaus and P. Winzer, "Hollow-core fiber capacities with receiver noise limitations," in Optical Fiber Communications Conference and Exhibition (OFC), 2022, pp. 1-3.

[12] “NEC to build a transatlantic cable,” in https://www.nec.com/en/press/202110/global_20211008_01.html, 2021

[13] O. V. Sinkin, Alexey V. Turukhin, Yu Sun et al., "SDM for Power-Efficient Undersea Transmission," J. Lightwave Technol. 36, 361-371 (2018).

[14] P. Poggiolini, G. Bosco, A. Carena et al., "The GN-Model of Fiber Non-Linear Propagation and its Applications," in J. of Lightwave Technol. 32, 694-721 (2014).

[15] M. A. Bolshtyansky, J.-X. Cai, C. R. Davidson et al., "Impact of Spontaneous Guided Acoustic-Wave Brillouin Scattering on Long-haul Transmission," in Optical Fiber Communication Conference, OFC 2018, pp. 1-3.

[16] A. Bononi, J. -C. Antona, M. Lonardi, A. Carbo Meseguer and P. Serena, "The Generalized Droop Formula for Low Signal to Noise Ratio Optical Links," in J. of Lightwave Technol. 38, 2201-2213 (2020).

[17] A. Carbo Meseguer et al., "Experimental Assessment of Capacity Prediction from G-SNR measurements for Submarine Systems," in Optical Fiber Communications Conference and Exhibition (OFC), 2022, pp. 1-3.

[18] T. Frisch and S. Desbruslais. “Electrical Power, a Potential limit to cable capacity.” in SubOptic Conference, 2013, pp. 1-3.

[19] J. Antona, A. Carbo Meseguer and V. Letellier, "Evolution of High-Capacity Submarine Open Cables," 2019 Asia Communications and Photonics Conference (ACP), 2019, pp. 1-3.

[20] V. M. C. Mathias, A. Carbó Meseguer et al., "Extension of the Measurement-Based Gain Model for non-Flat WDM Inputs and various pump currents,” in 2021 *European Conference on Optical Communication (ECOC)*, 2021, pp. 1-3.

[21] Lutz Rapp and Michael Eiselt, “Optical Amplifiers for Wideband Optical Transmission Systems,” in Optical Fiber Communications Conference and Exhibition (OFC), 2021, pp. 1-3.