Cable Capacity and Cost/bit Modeling of Submarine MCF Systems with MC-EDFA Alternatives

John D. Downie, Yongmin Jung, Sergejs Makovejs, Merrion Edwards, and David J. Richardson

***Abstract*— We model and examine various amplification options for trans-oceanic repeatered submarine systems using multicore fiber (MCF) transmission in the context of relative cable capacity and relative system cost/bit. First, we compare the optical performance of various configurations of parallel standard single-core erbium-doped fiber amplifiers (SC-EDFAs) and multicore erbium-doped fiber amplifiers (MC-EDFAs), including both the C/L-bands and core/cladding pump designs. Key amplifier parameters governing expected capacity and cost/bit performance include noise figure, amplifier bandwidth, relative electrical-to-optical conversion efficiency, and relative amplifier cost. We make our best estimates of these parameters through modeling, analysis, and component cost estimates and assess the sensitivity of the results to the nominal values. We find that MC-EDFAs using either core- or cladding-pumping might offer lower cost/bit than parallel SC-EDFAs but cladding-pumping may reduce cable capacities due to the higher noise figure and potentially smaller amplifier bandwidth.**

***Index Terms*—Optical fiber cables, optical fiber amplifiers, submarine cables, cable capacity, multicore fiber.**

I. Introduction

Traffic growth in trans-oceanic undersea systems has grown rapidly in recent years and this growth appears to continue unabated [1]. This creates continuing demand for submarine cables with ever greater capacities. At the same time, it is always necessary to minimize system cost/bit for viable system techno-economics. These requirements for higher capacity and lower cost/bit have led naturally to the cable concept of space division multiplexing (SDM) in which the limited electrical power is distributed over more spatial paths in the cable [2-7]. Both theoretical and experimental studies have demonstrated that power efficiency (and thus capacity for fixed power supply) can be significantly enhanced in this manner [8-11], at least up to limits imposed by signal droop effects [12,13]. To date, this industry design approach has followed an evolutionary path by deploying larger numbers of single-core fibers (SCFs), from traditional designs with 2-6 fiber pairs (FPs) to 8, 16, and now up to 24 FPs of standard diameter fiber (~250 μm). The next step in cable capacity growth is likely to be with 200 μm diameter fibers that may allow 32-36 FPs to be deployed in current cable designs [14,15]. However, to enable continued cable capacity growth and to achieve ≥1 Pb/s cables will require further fiber and system innovations. This will likely come from either additional reduction of SCF diameter [16,17] or multicore fibers (MCFs) [18,19].

MCF is a fiber technology that has been studied intensively in the past decade and has attracted great interest in the submarine cable community as a means to achieve even higher density of spatial paths than is likely possible with SCFs. Current MCF designs considered potentially suitable for submarine systems generally have 2 cores or 4 cores [20,21]. It is likely that at least initial deployments of MCF in submarine systems would achieve amplification in repeaters using conventional single-core erbium-doped fibre amplifiers (SC-EDFAs) with fan-in/fan-out (FIFO) devices at the input and output ends of the repeaters [22,23]. This type of configuration may be sufficient for 2-core MCF systems. However, systems built with 4-core (or > 4) MCFs may run into space limitations in repeaters with the parallel SC-EDFA approach, motivating continuing research in MC-EDFAs, and indeed recent work has demonstrated MCF cable transmission tests using MC-EDFAs [21].

In this work, we focus on potential submarine cable systems using MCF transmission fiber and we evaluate overall cable capacity and relative system cost/bit through the modeling of different amplification options. Since the need for amplification alternatives may be greater for MCFs with 4 cores, we consider that fiber type for the transmission system. The baseline amplification configuration used as a reference is that with parallel SC-EDFAs and FIFO devices. Through enhanced integration, MC-EDFAs may offer valuable repeater space savings and potentially other benefits. Here, we compare MC-EDFAs using core-pumping and cladding-pumping against the baseline, with assumptions about feasible critical parameters such as noise figure (NF), electrical-to-optical (E-O) conversion efficiency, and relative costs. The analysis evaluates the sensitivity to these assumptions and suggests the ranges of cable capacity and relative cost/bit enabled by the

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different options. This paper is an expanded version of a previous conference paper [24]. Compared to [24], we significantly expand on the description of the various MC-EDFA designs with details about how critical parameters were estimated and determined, including relative EDFA cost, relative E-O conversion efficiency, noise figure, and bandwidth. We also include FIFO costs in the analysis that were neglected earlier, and present new results for a second system design objective of overall cost/bit minimization.

The remainder of this paper is organized as follows: in section II we describe the systems modeled and provide details on the parameter assumptions made for the MC-EDFA configurations. We present the modeling results and discussion in section III, and then a summary and conclusions are given in section IV.

II. SYSTEM AND MODEL ASSUMPTIONS

The primary system link length considered for this analysis was a 7,000 km trans-Atlantic type link. Two different system design objectives were studied. The first objective was to maximize the system cable capacity for a fixed span length with a fixed number of fiber pairs, and the second objective addressed was to minimize the overall system cost/bit by searching over span length and number of fiber pairs. Currently, the largest cable voltage applied for single-ended powering is 18 kV so we used this value here for our modeling since very large capacity cables using MCF will consume large amounts of power. The level of power that can be delivered to the repeaters is dependent on both the cable voltage and the cable conductor resistance. Lower resistance provides greater electrical power for use in the repeaters to drive the amplifiers. A cable resistance value of 0.7 Ω/km was used in this analysis for the first design approach, at the low end of practical cable conductors today, again to create maximum power delivery conditions for an MCF system.

The MCF assumed for the transmission link was a 4-core MCF. The cores were nominally uncoupled, each with uniform attenuation of 0.160 dB/km and effective area of 82 μm^2. The baseline or reference amplification scheme illustrated in Fig. 1 employed 4 parallel conventional SC-EDFAs with FIFO devices on each side to connect the transmission MCF with the SC-EDFAs. The FIFOs had 0.3 dB average loss and generated -50 dB crosstalk per individual device (fan-in or fan-out). Both of these parameters may be slightly conservative, as we note that FIFO values below 0.15 dB have been recently demonstrated [25], but losses in large scale manufacturing could be somewhat higher.

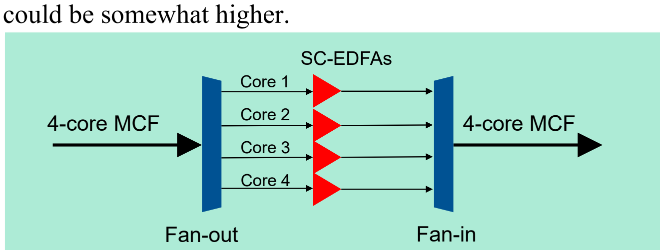

Fig. 1. Baseline amplifier case with FIFOs and parallel SC-EDFAs.

The basic system cost/bit model used in this work follows from earlier work [21,22] with further description details provided in [22]. We base cost estimates on the wet plant only with contributions for fiber, repeaters, cable, and marine operations. In this model, the repeater costs are calculated based on amplifier costs. That is, while overall repeater costs were originally cast in terms of the number of fiber pairs for a system using single-core fibers, we converted this into a per amplifier cost to allow variation over a range of fiber pairs, or in this case, fiber core pairs. As we will later estimate the relative amplifier costs of MC-EDFAs against SC-EDFAs and use those relative values in the cost/bit modeling, we note that this approach may somewhat overemphasize the repeater cost dependence on amplifiers. However, we believe that the effect will be minor given the very large number of amplifiers involved in the MCF system. In the previous study [24], we ignored the FIFO costs because they were assumed to be fairly small compared to the other cost factors. We include the FIFO costs here with a conservative estimate based on what we believe are currently available when purchased in small numbers. Large scale production of FIFOs would almost certainly result in cost reduction so more realistic conditions would likely produce cost/bit results somewhere between the earlier results in [24] and those found here, serving as boundaries for the dependence on FIFO costs.

Fiber capacities and thus total cable capacities are calculated using the Gaussian Noise (GN) model [26,27] for coherent transmission in dispersion-unmanaged systems. We use a pump sharing model as described in [28] for SC-EDFAs that estimates overall electrical-to-optical (E-O) conversion efficiency as a function of repeater power, EDFA output power, and span loss. For the MC-EDFAs, we modify the E-O conversion efficiency from the baseline by the relative efficiency penalty incurred by the MC-EDFA configuration (if any) as described shortly.

As shown in Fig. 2, three different fiber amplifier configurations capable of realizing simultaneous amplification of multiple spatial channels are considered in this study. Note that 4-core fibers are used in both core- and cladding-pumped MC-EDFAs with a standard outer clad/coating diameter of 125/250 μm compatible with existing submarine cables and a pump resilience of 2 is applied to create pump route diversity and improved reliability.

First, we evaluated the potential cost-saving benefits of MC-EDFAs compared to parallel SC-EDFAs based on the current available technology and likely component cost estimations, summarized in Table I. Here, we assumed that passive MCF components cost twice as much as SCF devices because they require rotational alignment during fabrication. Note that polarization maintaining fiber components currently cost 2× more than SCF devices due to the need for rotational alignment and it is reasonable to expect MCF components to be at a similar price premium because they will ultimately require similar manufacturing complexity. Note that the absolute cost numbers

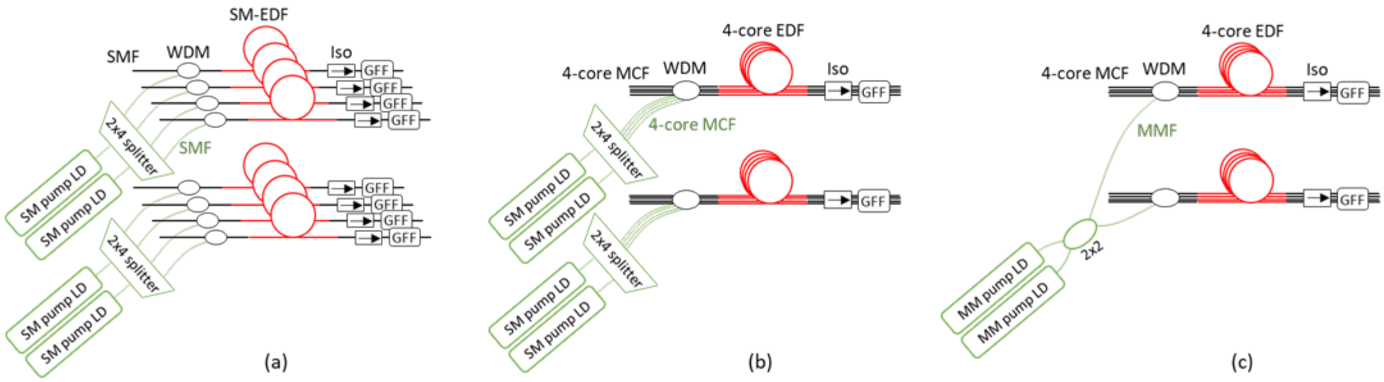

Fig. 2. Three different fiber amplifier configurations for multi-spatial channel amplification: a) parallel SC-EDFAs, b) core-pumped MC-EDFAs and c) cladding-pumped MC-EDFAs.

we are using are based on quotes for one-off type purchases, but we anticipate substantial cost saving when buying in volume. We contend that the likely bulk cost saving factors will be similar for all components meaning that the relative cost reduction estimates for the different amplifier builds should be reasonable. We consider that the price of the EDF will be dominated by the cost of the doped core glass material and hence that the material cost of a 4-core EDF should reasonably be expected to be 4× that of a SC-EDF. However, MCF fabrication itself requires additional fabrication processes (e.g., according to current stack-and-draw or drilling methods), and hence is expected to be significantly more expensive than SCF. However, due to the relatively short fiber length needed to fabricate an EDFA, we have assumed that the total cost of 4-core EDF is likely to be 1.5× the material cost (by material cost we refer to the base material costs + fabrication steps required to produce the core preforms). In terms of pump diodes and current driver modules for the core- and cladding-pumped configurations, 500 mW fiber pigtailed single mode pump laser diodes (LDs) and 10 W capable multimode pump diodes are considered. Here, note that the price of the pump LDs (both for single mode and multimode technologies) is typically determined in terms of $/W. The cost of multimode pump LDs is much lower than that of single mode pump LDs in terms of $/W (approximately 50-60 times cheaper). Based on our considered estimates of likely relative component costs for the 3 different amplifier configurations we anticipate ~15% capital expenditure (CAPEX) cost saving benefit from device integration in core-pumped MC-EDFAs and ~50% in cladding-pumped MC-EDFAs (with some scope to further improve this to ~70%). The greater price savings of cladding-pumped MC-EDFAs is mainly due to the use of low-cost multimode pump LDs and the need for a lesser number of pump LDs, current drivers and fiber components.

TABLE I

COST SAVING BENEFITS OF MC-EDFAS

	Parallel SC-EDFA [$]	Core-pumped MC-EDFA [$]	Cladding-pumped MC-EDFA [$]
Fiber components	8,000	4,800	4,800
EDFs	1,200	1,800	1,800
Pump LDs & drivers	8,000	8,000	1,700
Total	17,200	14,600	8,300
Cost benefit	1	0.85	0.48

Secondly, we analyzed the E-O conversion efficiency of the MC-EDFAs compared to parallel SC-EDFAs and the results of our assessment are summarized in Table II. As detailed in references [28,29], the overall E-O conversion efficiency of submarine repeaters can be calculated as $\eta = \eta_{driver} \cdot \eta_{aging} \cdot \eta_{pump} \cdot \eta_{EDF} \cdot \eta_{GFF}$, where η_{driver} is the efficiency of the electrical current driver, η_{aging} accounts for the current required to accommodate pump LD aging over a 25-year lifespan, η_{pump} is the E-O conversion efficiency of the pump LD, η_{EDF} is the optical power conversion efficiency (OPCE) of the erbium doped fiber and η_{GFF} is the associated power loss due to the use of a gain flattening filter (GFF). Here, the E-O conversion efficiency of the pump LD and the OPCE of the EDF are the most important differentiating factors that lead to the difference in the overall amplifier efficiency between architectures. In our detailed power consumption estimates, E-O conversion efficiencies of ~30% and ~45% were used as typical values for single- and multi-mode pump LDs, respectively [30,31]. For the OPCE estimation of EDFs, to ensure a fair performance comparison across the various optical amplifier configurations, we modelled their relative performance using a commercial optical amplifier simulator (OptiSystem) [32] and compared the predictions to experimental data in the literature to provide added confidence in the results [33,34]. Note that we examined both core- and

TABLE II

POWER CONSUMPTION OF MC-EDFAS IN CORE- AND CLADDING-PUMPED CONFIGURATIONS

	Band	Composition of EDF	Pump LD	Driver efficiency (η_{driver})	Current for pump aging (η_{aging})	Pump LD E-O efficiency (η_{pump})	OPCE of EDF (η_{EDF})	Gain flattening filter (η_{GFF})	Overall amplifier efficiency (η)	Efficiency penalty compared to SC-EDFA
Core-pumped EDFA	C-band	Er	SM980nm	33%	67%	~30%	~50%	50%	1.6%	-
	L-band	Er	SM950nm			~30%	~30%		0.9%	~40%
Cladding-pumped EDFA	C-band	Er/Yb	MM980nm			~45%	~30%		1.5%	~10-15%
	L-band	Er	MM980nm			~45%	~30%		1.5%	~10-15%

cladding-pumped MC-EDFA configurations operating in both the C- and L-bands with appropriate rare earth ion/host dopants and pump wavelengths for each pumping approach as shown in Table II. In general, the OPCE of an amplifier strongly depends on the input signal power and it improves as the input signal power increases. Therefore, in our simulations, we fixed the input signal power to 0 dBm and then compared the relative OPCEs of the various amplifier configurations. In the case of core-pumped MC-EDFAs, we estimated a OPCE of ~50% in the C-band and ~30% in the L-band. The lower L-band OPCE is mainly due to strong backward propagating C-band amplified spontaneous emission (ASE) at the input port of the EDF. Moreover, a proper choice of pump wavelength (e.g. 950-960 nm, which is ~20-30nm away from the pump absorption peak at 980 nm, or 1480 nm) [35] is very important for efficient L-band amplification. In cladding-pumped MC-EDFAs, ~30% OPCE is readily achievable in both the C- and L-bands. Note however that erbium-only doped fibers are generally inefficient for C-band amplification in cladding-pumped configurations due to the relatively low absorption cross section of Er (OPCE< a few %) and ytterbium-sensitized EDFs (called Er/Yb co-doped fibers) [36] are used to enhance pump absorption and to increase the amplifier efficiency. As shown in Table II, we expect core-pumped MC-EDFAs to have no appreciable overall E-O efficiency penalty relative to the use of multiple SC-EDFAs. Conversely, we estimate a ~10-15% E-O efficiency penalty for cladding-pumped MC-EDFAs compared to conventional C-band SC-EDFAs. Moreover, according to our modelling, we expect cladding-pumped C-band MC-EDFAs to have a slightly reduced bandwidth (i.e. 30 nm for the C-band due to the requirement for Er/Yb co-doping) versus 35 nm for L-band operation (where Er-only doping can still be used). However, for both C&L band cladding-pumped devices we estimate an increased noise figure of ~6 dB (due to the lower population inversions achievable given the relatively low brightness pumping). Table III summarizes the nominal parameters used for the different amplifier configurations.

For the system modeling in the next section, we assumed 100 Gbaud signals with 44 channels corresponding to the 35 nm bandwidth, and 38 channels corresponding to the 30 nm bandwidth.

TABLE III

NOMINAL AMPLIFIER PARAMETERS

	SC-EDFA	Core-pumped MC-EDFA	Cladding-pumped MC-EDFA	
Band	C-band	C-band	C-band	L-band
BW (nm)	35	35	30	35
NF (dB)	5	5	6	6
E-O efficiency Penalty (%)	-	0	15	15
EDFA cost reduction (%)	-	15	50	50

III. MODELING RESULTS AND DISCUSSION

To begin, we examined the performance of MC-EDFAs compared to the baseline case with parallel SC-EDFAs and FIFO as a function of the two main variables E-O conversion efficiency penalty and EDFA cost reduction if NF and amplifier bandwidth can be maintained equal to SC-EDFAs. According to our assumptions summarized in Table III in the previous section, equal NF and bandwidth is reasonable for core-pumped MC-EDFAs but not for cladding-pumped MC-EDFAs. The system length was 7,000 km. The objective was maximization of cable capacity with 16 FPs (64 core pairs). The behavior of cable capacity depends only on the E-O efficiency penalty and this dependence is shown in Fig. 3. The results are presented normalized to the capacity of the baseline system with parallel SC-EDFAs. For no efficiency penalty such as expected with a core-pumped MC-EDFA, there is a capacity gain of approximately 8% due to the elimination of the FIFOs. An E-O efficiency penalty of about 15% would yield the same cable capacity as the baseline, and larger penalties would result in smaller cable capacities. The relative cost/bit of the hypothetical MC-EDFA systems to the cost/bit of the baseline system is shown as a function of both variables in Fig. 4. The thick solid line represents cost/bit parity between the MC-EDFA and parallel SC-EDFA systems with all points below the line representing lower system cost/bit for the MC-EDFA systems. The solid blue circle represents the expected performance of a core-pumped MC-EDFA system and the red circle is that of an ideal cladding-pumped MC-EDFA system with equal NF and bandwidth to the baseline SC-EDFA system. Those points suggest a system cost/bit advantage of ~16% for the core-pumped MC-EDFA, and ~25% for the cladding-pumped MC-EDFA under these conditions. These values are approximately 2% greater than the values obtained in [24] when the cost of FIFOs was neglected.

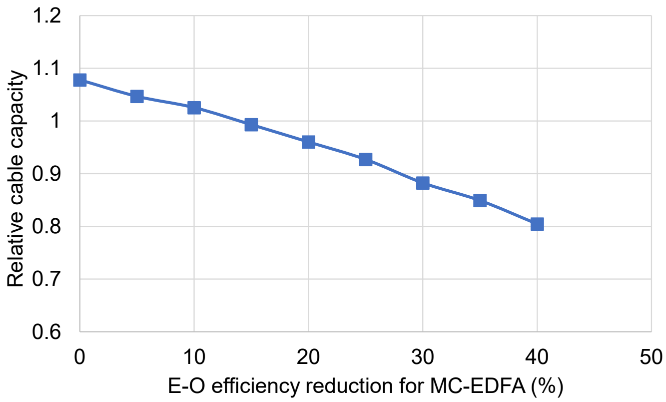

Fig. 3. Relative cable capacity as a function of E-O efficiency reduction of MC-EDFAs. Results are normalized to the baseline system case.

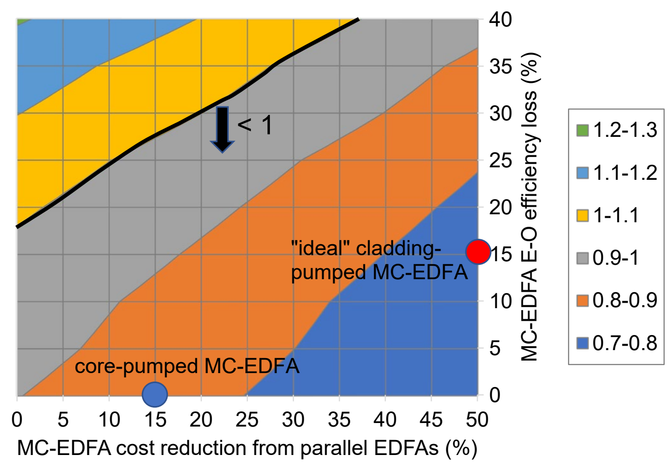

Fig. 4. Relative system cost/bit of MC-EDFA system to baseline SC-EDFA system as functions of MC-EDFA cost reduction and E-O efficiency penalty.

We next apply the nominal MC-EDFA parameters expressed in Table III including higher NF for the cladding-pumped amplifiers and smaller bandwidth for the C-band cladding-pumped amplifier. The results are shown in Fig. 5 for the cable capacities predicted and the relative cost/bit normalized to the value of the baseline case with parallel SC-EDFAs. Because the core-pumped MC-EDFA eliminates the losses of the FIFOs but is assumed to have no E-O conversion efficiency penalty and the same bandwidth and NF, this amplifier type can offer slightly higher cable capacity than the baseline. On the other hand, the higher NF of the cladding-pumped MC-EDFAs reduces the cable capacity, as does the smaller bandwidth of the C-band cladding-pumped configuration to a lesser extent. The smaller bandwidth of that amplifier is somewhat mitigated by the higher channel powers allowed for the same 16 fiber pairs. Interestingly, all 3 types of MC-EDFAs appear to offer lower relative cost/bit compared to the baseline case, even for the cladding-pumped versions with lower cable capacity. This is a result of the significant amplifier cost savings projected of ~15% for the core-pumped MC-EDFA and 50% for the cladding-pumped MC-EDFAs. Under these nominal parameter assumptions, the core-pumped MC-EDFA enables more than 15% overall system cost/bit reduction, while the reductions may be in the range of 9-12% for the cladding-pumped amplifiers.

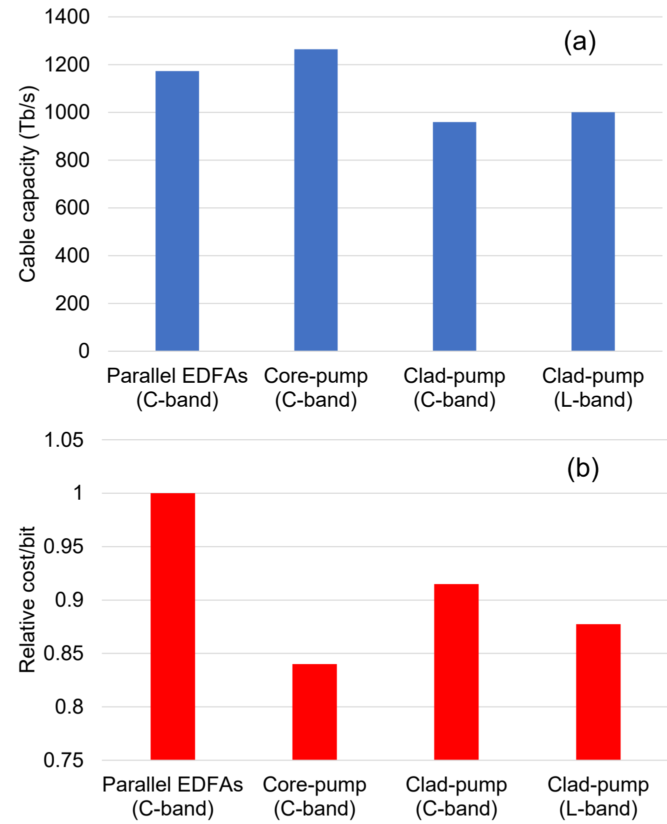

Fig. 5. (a) Cable capacity values for different amplifier configurations in a 4-core MCF system. (b) Relative cost/bit values of the amplifier configurations..

While the basic results corresponding to the nominal parameters are given in Fig. 5, it is helpful to assess the sensitivity to the major parameters since they are not known with precision. In Fig. 6, the dependence of the relative cost/bit normalized to the baseline case as a function of MC-EDFA cost reduction is shown. The nominal E-O efficiency penalties are applied. The results show that at least 35-40% amplifier cost reduction is needed for cladding-pumped MC-EDFAs to achieve cost/bit parity with the baseline, while a significant 20% cost/bit advantage may be possible if the MC-EDFA cost savings is as high as 70%. On the other hand, there appears to be significant latitude in the MC-EDFA cost reduction for the core-pumped MC-EDFA to achieve lower system cost/bit than the baseline. According to these results, core-pumped MC-EDFAs may still enable some cost/bit advantage even if the cost is the same or even slightly higher (negative cost reduction in the figure) than the parallel SC-EDFA configuration. For reference, the nominal values of the MC-EDFA cost reduction are also illustrated in Fig. 6 by the blue arrows.

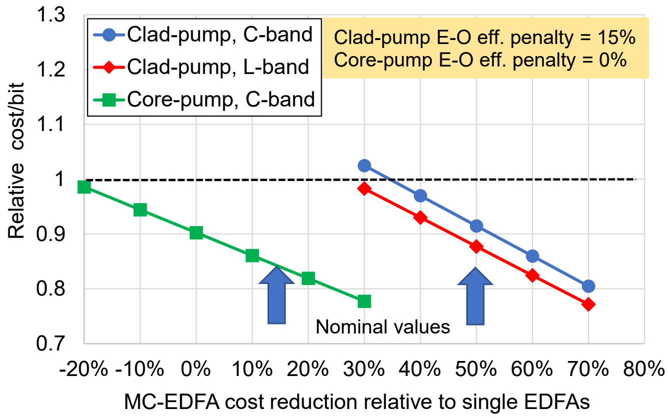

Fig. 6. Relative system cost/bit as a function of MC-EDFA cost reduction compared to baseline case.

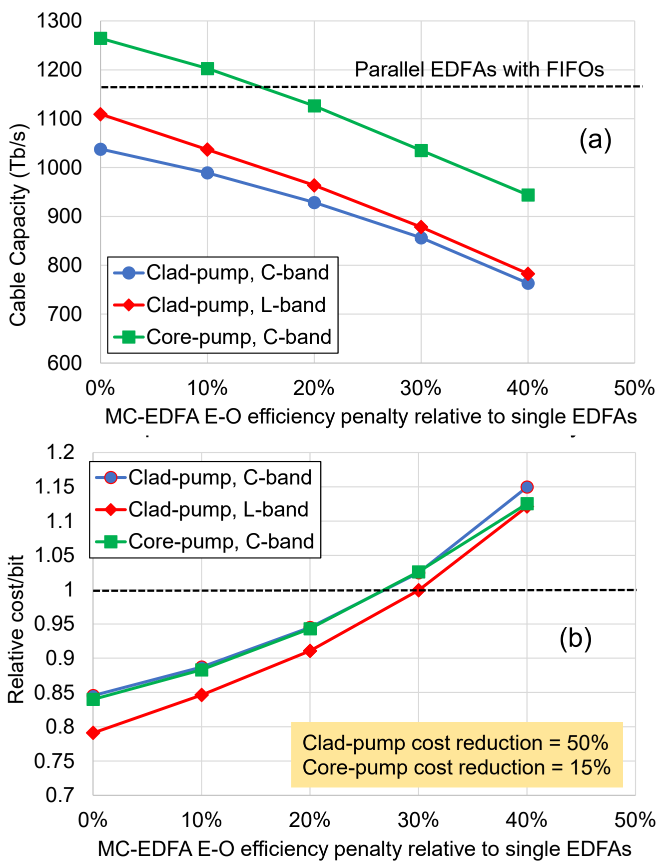

Fig. 7. (a) Cable capacity and (b) relative system cost/bit as functions of MC-EDFA E-O efficiency penalty relative to parallel SC-EDFAs.

Fig. 7 has results illustrating the sensitivity of both cable capacity and relative system cost/bit as functions of MC-EDFA E-O efficiency penalty. Dashed horizontal lines in both figures represent the levels of the baseline case. The results suggest that the MC amplifier E-O efficiency penalties should be no higher than about 25% for all MC-EDFA types to enable some relative cost/bit advantage to the baseline. Recall that our nominal assumptions are no E-O penalty for the core-pumped MC-EDFA and about a 15% penalty for the cladding-pumped MC-EDFAs. However, even if cladding-pumped MC-EDFAs had no penalty, the expected cable capacities would still be smaller than the baseline due to the higher NF and smaller C-band bandwidth.

The previous results were obtained when maximizing the total cable capacity by deploying 16 fiber pairs of 4-core MCF with a fixed span length of 70 km. In the next approach, we design the systems with an objective of minimizing the overall cost/bit for each system with different amplifier types. This is done as a function of conductor resistance value with 18 kV cable voltage. In this approach, we optimize the designs by finding the optimal number of fiber pairs and optimal span length that minimize system cost/bit for each resistance value. The span length is determined with a granularity of 10 km in the range from 50 km to 100 km. We use the nominal MC-EDFA parameters as given in Table III. The relative cost/bit and corresponding cable capacity results of this approach are given in Fig. 8 for the 7,000 km link. The relative cost/bit results are normalized to the parallel SC-EDFA baseline case with 0.7 Ω/km cable resistance. The optimal number of 4-core MCF fiber pairs as a function of resistance is given for each amplifier type in Fig. 9. One observation is that the relative cost/bit of the C-band core-pumped MC-EDFA and the L-band cladding-pumped MC-EDFA systems are nearly the same for any cable resistance and that both have about a 15-16% reduction compared to the baseline case. However, the cable capacities of those two systems are quite different as the core-pumped MC-EDFA systems offer significantly higher capacity on the order of 20-30%. We also note that the optimal number of fiber pairs is not 16, even for the lowest cable resistance of 0.7 Ω/km. The largest optimal number of FPs is always for the core-pumped MC-EDFA systems while the lowest number is always for the L-band cladding-pumped MC-EDFA systems. This may be at least partly due to the fact that the optimal span length was 70 km in all cases for the core-pumped MC-EDFA while it was 60 km for the L-band cladding-pumped MC-EDFA.

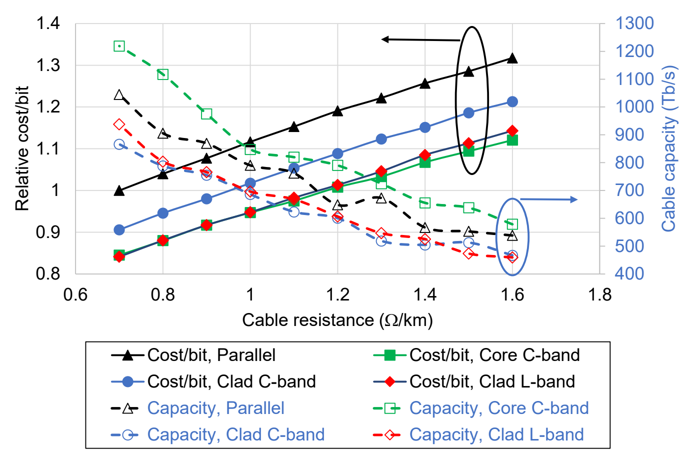

Fig. 8. Relative system cost/bit and corresponding cable capacity as functions of cable resistance with minimum cost/bit as the design objective.

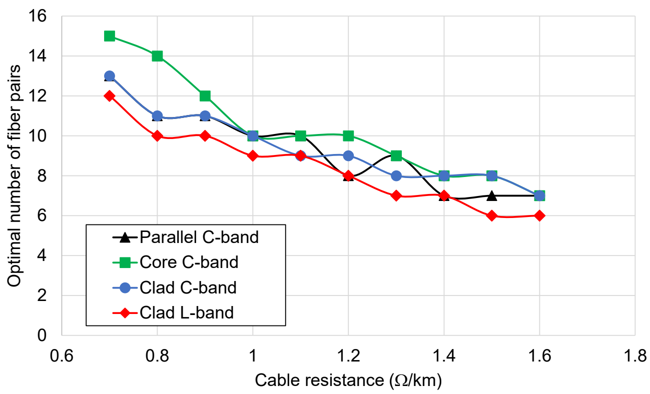

Fig. 9. Optimal number of MCF fiber pairs minimizing overall cost/bit as a function of cable resistance.

IV. SUMMARY AND CONCLUSIONS

We have examined several different amplification options for MCF submarine transmission systems in terms of cable capacity and relative system cost/bit. We studied two different system design objectives, namely 1) maximizing cable capacity and 2) minimizing overall cost/bit and found both approaches produced similar results. We found that both core-pumped MC-EDFAs and cladding-pumped MC-EDFAs may offer a small (~15% or less) system cost/bit advantage relative to the baseline case of parallel SC-EDFAs with FIFOs. Inclusion of FIFO costs at current low-volume levels seems to affect the relative techno-economic performance of the baseline case by about 2% [24]. Cladding-pumped MC-EDFAs always produce total cable capacities lower than the baseline configuration or core-pumping due to higher NF, an E-O conversion efficiency penalty, and a slightly narrower gain bandwidth in the case of C-band operation. On the other hand, core-pumped MC-EDFAs can offer the same E-O efficiency as SC-EDFAs and allow the elimination of FIFO losses, thereby enabling higher cable capacity of about 5-10%. These results suggest that core-pumped MC-EDFAs may be a preferred solution for MCF submarine systems, at least for MCFs with 4 or more cores. We did not consider the effects of core-core gain variation in this study, which would likely be more significant and detrimental for cladding-pumped amplifiers than core-pumped amplifiers due to lack of independent core controls [37]. This prospect, along with the historically proven reliability of single-mode pump lasers in comparison to high power multimode pump lasers further supports the case for core-pumped MC-EDFAs for future MCF systems. While the results obtained here were for the case of 16 FPs (64 core pairs), we do not expect significant differences in the relative capacity and cost/bit for larger FP counts producing greater cable capacities.

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REFERENCES

[1] S. Grubb, "Submarine cables: Deployment, evolution, and perspectives," *Optical Fiber Communication Conference (OFC)*, 2018, paper M1D.1.

[2] A. Pilipetskii, D. Foursa, M. Bolshtyansky, G. Mohs, and N. S. Bergano, "Optical designs for greater power efficiency," in *Proceedings SubOptic 2016*, Dubai 2016, paper TH1A.5.

[3] S. Desbruslais, "Maximizing the capacity of ultra-long haul submarine systems," *2015 20th European Conference on Networks and Optical Communications - (NOC)*, 2015, pp. 1-6, doi: 10.1109/NOC.2015.7238603.

[4] E. Mateo, Y. Inada, T. Ogata, S. Mikami, V. Kamalov, V. Vusirikala, "Capacity limits of submarine cables," in *Proceedings SubOptic 2016*, Dubai 2016, paper TH1A.1.

[5] O. D. Domingues, D. A. A. Mello, R. da Silva, S. Ö. Arık and J. M. Kahn, "Achievable Rates of Space-Division Multiplexed Submarine Links Subject to Nonlinearities and Power Feed Constraints," *J. Lightwave Technol.*, vol. 35, no. 18, pp. 4004-4010, 15 Sept.15, 2017, doi: 10.1109/JLT.2017.2720541.

[6] A. N. Pilipetskii and G. Mohs, "Technology Evolution and Capacity Growth in Undersea Cables," *2020 Optical Fiber Communications Conference and Exhibition (OFC)*, 2020, pp. 1-3, paper W4E.2.

[7] R. Dar, P. J. Winzer, A. R. Charaplyvy, S. Zsigmond, K.-Y. Huang, H. Fevrier, and S. Grubb, "Cost-optimized submarine cables using massive spatial parallelism," *J. Lightwave Technol.*, vol. 36, no. 18, pp. 3855–3865, September 2018, doi: 10.1109/JLT.2018.2841810.

[8] A. Turukhin, O. V. Sinkin, H. G. Batshon, H. Zhang, Y. Sun, M. Mazurczyk, C. R. Davidson, J. X. Cai, M. A. Bolshtyansky, F. G. Foursa, and A. Pilipetskii, "105.1 Tb/s power-efficient transmission over 14,350 km using a 12-core fiber," *Optical Fiber Communications Conference (OFC)*, 2016, paper Th4C.1.

[9] J. D. Downie, "Maximum Capacities in Submarine Cables with Fixed Power Constraints for C-Band, C+L-Band, and Multicore Fiber Systems," *J. Lightwave Technol.*, vol. 36, no. 18, pp. 4025-4032, 15 Sept.15, 2018, doi: 10.1109/JLT.2018.2858194.

[10] P. J. Winzer, "Energy-Efficient Optical Transport Capacity Scaling Through Spatial Multiplexing," *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 851-853, July1, 2011, doi: 10.1109/LPT.2011.2140103.

[11] R. Essiambre and R. W. Tkach, "Capacity Trends and Limits of Optical Communication Networks," in *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1035-1055, May 2012, doi: 10.1109/JPROC.2012.2182970.

[12] A. Bononi, J.-C. Antona, M. Lonardi, A. Carbo-Meseguer, P. Serena, "The generalized droop formula for low signal to noise ratio optical links" *J. Lightwave Technol.,* vol. 38, no. 8, pp. 2201–2213, Apr. 2020, DOI: 10.1109/JLT.2020.2966145.

[13] J. D. Downie, X. Liang, V. Ivanov, P. Sterlingov and N. Kaliteevskiy, "SNR Model for Generalized Droop With Constant Output Power Amplifier Systems and Experimental Measurements," *J. Lightwave Technol.*, vol. 38, no. 12, pp. 3214-3220, 15 June15, 2020, doi: 10.1109/JLT.2020.2996061.

[14] T. Inoue, K. Nakamura, Y. Matsuo, F. Yaman, S. Makovejs, J. T. Prater, J. C. Aquino, D. Masuda, Y. Inada, E. Mateo, "200µm Diameter Fiber for SDM Submarine Networks: Cabling Performance and Record Transmission Result," *Optical Fiber Communications Conference (OFC),* 2022, paper. M1F.3.

[15] J. D. Downie, X. Liang, J. Hurley, J. Prater, D. Robbins, D. Stainer, K. Synowiec, "200 µm Diameter Ultra-Low-Loss Optical Fiber for High-Density Submarine and Terrestrial Applications," *Advanced Photonics Congress* 2022, paper SpM3J.1.

[16] M.-J. Li, A. Abedijaberi, W. Niu, E. E. Leonhardt, D. A. Clark, G. W. Scannell, M. R. Drake, J. S. Stone, J. E. McCarthy, A. L. Wallace, H. Deng, L. S. Baker, H. M. De Pedro, B. A. Kent, Y. Gu, "Reduced Coating Diameter Fibers for High Density Cables," *Optical Fiber Communications Conference (OFC)*, 2022, paper M4E.1.

[17] S. R. Bickham *et al.*, "Ultra-Low-Loss Reduced-Clad Fiber with Attenuation less than 0.16 dB/km," *Proc. OECC 2022*, Paper PDP-A-2.

[18] T. Hayashi, Y. Tamura, H. Sakuma, Y. Koyano, and T. Hasegawa, "Low-loss multi-core fibers for submarine transmission," in *Proceedings SubOptic 2019*, New Orleans 2019, paper OP10-3.

[19] T. Gonda, K. Imamura, K. Kawasaki, R. Sugizaki, S. Arai, M. Tsukamoto, and M. Shiino, "Recent progress and outlook on multicore fiber for practical use," *Optical Fiber Communications Conference (OFC)*, 2018, paper Tu3B.1.

[20] Y. Tamura *et al*, "Low-loss uncoupled two-core fiber for power efficient practical submarine transmission," *OFC'19*, 2019, paper M1E.5.

[21] H. Takeshita, K. Nakamura, Y. Matsuo, T. Inoue, D. Masuda, T. Hiwatashi, K. Hosokawa, Y. Inada, E. Le Taillandier de Gabory, "First Demonstration of Uncoupled 4-Core Multicore Fiber in a Submarine

Cable Prototype with Integrated Multicore EDFA," *Optical Fiber Communications Conference (OFC)*, 2022, paper M4B.1.

[22] J. D. Downie, X. Liang, S. Makovejs, "Techno-Economic Analysis of Multicore Fibers in Submarine Systems," *Optical Fiber Communications Conference (OFC)*, 2021, paper Th4C.4.

[23] J. D. Downie, X. Liang and S. Makovejs, "Modeling the Techno-Economics of Multicore Optical Fibers in Subsea Transmission Systems," *J. Lightwave Technol.,* vol. 40, no. 6, pp. 1569-1578, 15 March15, 2022, doi: 10.1109/JLT.2021.3123900.

[24] J. D. Downie et al, "Modelling of Cable Capacity and Relative Cost/bit Between Amplification Options for Submarine MCF Systems," *ECOC'22*, 2022, paper Mo4D.4.

[25] V. I. Kopp, J. Park, J. Singer, D. Neugroschl, T. Suganuma, T. Hasegawa, T. Ohtsuka, H. Tazawa, "Ultra-Low-Loss MCF Fanouts for Submarine SDM Applications," *Optical Fiber Communications Conference (OFC)*, 2022, paper Th1E.2.

[26] P. Poggiolini, "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *J. Lightwave Technol*., vol. 30, no. 24, pp. 3857-3879, Dec.15, 2012, doi: 10.1109/JLT.2012.2217729.

[27] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang and F. Forghieri, "The GN-Model of Fiber Non-Linear Propagation and its Applications," *J. Lightwave Technol*., vol. 32, no. 4, pp. 694-721, Feb.15, 2014, doi: 10.1109/JLT.2013.2295208.

[28] X. Liang, J. D. Downie and J. E. Hurley, "Repeater Power Conversion Efficiency in Submarine Optical Communication Systems," *IEEE Photonics J.*, vol. 13, no. 1, pp. 1-10, Feb. 2021, Art no. 7901110, doi: 10.1109/JPHOT.2021.3054624.

[29] T. Frisch and S. Desbruslais, "Electrical power, a potential limit to cable capacity," *in Proc. SubOptics 2013*, 2013, paper TU1C-04.

[30] https://www.thorlabs.com/drawings/b2dbfe7f022f8e56-2F5AAC93-E2BA-CDB1-D72877A2A604E21E/BL976-PAG500-SpecSheet.pdf

[31] https://www.ipgphotonics.com/en/640/Widget/PLD-10+Diode+Laser+Datasheet.pdf

[32] www.optiwave.com

[33] G. Melin, R. Kerampran, A. Monteville, S. Bordais, T. Robin, D. Landais, A. Lebreton, Y. Jaouen, T. Taunay, "Power efficient all-fiberized 12-core erbium/ytterbium doped optical amplifier," *Optical Fiber Communications Conference (OFC),* 2020, paper M4C.2.

[34] Y. Jung, M. Wada, K. Shibahara, S. Jain, I. A. Davidson, P. Barua, J. R. Hayes, T. Sakamoto, T. Mizuno, Y. Miyamoto, Y. Sasaki, K. Saitoh, K. Nakajima, D. J. Richardson, "High Spatial Density 6-Mode 7-Core Fiber Amplifier for L-Band Operation," *J. of Lightwave Technol.,* vol. 38, no. 11, pp. 2938-2943, 1 June, 2020, doi: 10.1109/JLT.2020.2976524.

[35] https://www.lightwaveonline.com/optical-tech/transport/article/16648168/pump-lasers-at-960-nm-for-the-lband

[36] G. G. Vienne, J. E. Caplen, L. Dong, J. D. Minelly, J. Nilsson, and D. N. Payne, "Fabrication and characterization of Yb3+:Er3+ phosphosilicate fibers for lasers," *J. of Lightwave Technol*., vol. 16, no. 11, pp. 1990-2001, November 1998.

[37] Y. Jung, S.-U. Alam, D. Richardson, S. Ramachandran, K.S. Abedin, "Multicore and multimode optical amplifiers for space division multiplexing," A. Willner (Ed.), Optical Fiber Telecommunications VII, Academic Press (2020), pp. 301-333, 10.1016/B978-0-12-816502-7.00008-7.

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