Modelling of Cable Capacity and Relative Cost/bit Between Amplification Options for Submarine MCF Systems

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Abstract *We examine amplification options for repeatered submarine systems using multicore transmission fibre in the context of relative cable capacity and system cost/bit. Multicore EDFAs using either core-pumping or cladding-pumping could offer lower cost/bit than parallel single-core EDFAs but cladding-pumping may reduce cable capacities. ©2022 The Author(s)*

Introduction

Traffic growth in trans-oceanic undersea systems has grown rapidly in recent years and this growth appears to continue unabated [1]. This has created the demand for submarine cables with greater capacities. At the same time, it is always necessary and imperative 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 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 fibres (SCFs), from traditional designs with 2-6 fibre pairs (FPs) to 8, 16, and now up to 24 FPs. However, to allow capacity growth much beyond that enabled by 24 FPs (e.g. to achieve ≥1 Pb/s cables) will require further system innovation. This will likely come from either reduced diameter SCFs [14,15] or multicore fibres (MCFs) [16,17].

Reduced diameter (200 μm) fibres are already available commercially and enable 24 FPs in small cable designs, and potentially allow fibre counts up to 32-36 FPs in standard size cables. Further reduction in diameter could enable higher fibre counts. MCF is another fibre technology that has generated great interest in the submarine cable community to achieve even higher density of spatial paths than might be possible with SCFs. It has largely been assumed 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 [18,19]. However, research continues in multicore EDFAs (MC-EDFAs), and recent work demonstrated MCF cable transmission tests using MC-EDFAs [20].

In this paper, we focus on potential submarine cable systems using MCF transmission fibre and we evaluate overall cable capacity and relative system cost/bit through the modelling of different amplification options. The baseline amplification configuration used as a reference is that with SC-EDFAs and FIFO devices. In principle, 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 different options.

System and Model Assumptions

The system modelled for this analysis was a 7,000 km link supplied with 18 kV cable voltage. A nominal cable resistance value of 0.7 Ω/km was assumed. The transmission fibre was an MCF with 4 cores. The MCF attenuation was 0.160 dB/km with total crosstalk of -60 dB/km. Each core effective area was 82 μm^2. For the baseline repeater amplification case using FIFO devices and conventional SC-EDFAs, the FIFO devices were assumed to have 0.3 dB loss and -50 dB crosstalk per device. The EDFAs had 5 dB noise figure (NF). We note that lower FIFO loss values of < 0.15 dB have been recently demonstrated [21], but we use a slightly higher value here to account for practical distributions.

The cost/bit model followed for this analysis has been previously described [18,19]. In this model, we use costs for the wet plant only, including contributions for fibre, repeaters, cable, and marine operations. The repeater costs are modelled on the basis of amplifier costs. We ignored the FIFO costs in this study. For the cases with MC-EDFAs, we applied the same amplifier cost model multiplied by a factor representing expected cost reduction or increase relative to SC-EDFAs. Total cable capacities are calculated using the Gaussian Noise (GN) model [22,23] for coherent transmission and a pump sharing model like that described in [24]. The pump sharing model allows estimation of overall E-O conversion efficiencies as a function of repeater power, EDFA output power, and span loss. For the MC-EDFAs studied, we modified the E-O conversion efficiencies from the baseline by another factor representing expected decreases in this parameter.

As mentioned, we treated systems with MC-EDFAs in this modelling by changing the relative amplifier costs and E-O conversion efficiencies. We also included any expected differences in noise figure between the baseline, core-pumped MC-EDFAs, and cladding-pumped MC-EDFAs. The nominal values for these parameters and explanations for their choices are described next.

First, to ensure a fair performance comparison across the various optical amplifier configurations we modelled their performance using a commercial optical amplifier simulator and compared the predictions to experimental data in the literature to provide added confidence in the results [25,26]. According to this modelling, cladding-pumped MC-EDFAs are expected to have slightly reduced bandwidth (30 nm for the C-band (due to the use of the erbium/ytterbium co-doping needed to ensure efficient operation in the C-Band) and 35 nm for L-band operation (based only on erbium doping)), an increased noise figure of ~6 dB (due to the lower population inversions achievable given the relatively low brightness pumping), and ~15% E-O efficiency penalty compared to conventional C-band SC-EDFAs (this estimate includes consideration of both the optical efficiency of the amplifier and the E-O conversion efficiency of multimode pump diode technology). We expect core-pumped MC-EDFAs to nominally have no efficiency penalty. Based on our considered estimates of likely relative component costs for the 3 different amplifier configurations we anticipate ~15% 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%). Table 1 summarizes the nominal parameters used for the different amplifier configurations.

Table 1: Nominal amplifier parameters

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

Results

For the results that follow, we assumed 44 channels at 100 Gbaud for a 35 nm optical bandwidth, and 38 channels for a 30 nm bandwidth. The systems were designed to maximize cable capacity with 16 fibre pairs of 4-core MCF and the span length was 70 km. To begin, we just explored the dependence on MC-EDFA relative cost reduction and relative E-O efficiency penalty if NF and bandwidth remain the same as SC-EDFAs at 5 dB and 35 nm, respectively. The results are shown in Fig. 1. The discrete blue circle represents the nominal case for a core-pumped MC-EDFA and the red circle represents an "ideal" cladding-pumped MC-EDFA. Both offer cost/bit reductions compared to the baseline, but realistic cladding-pumped amplifiers will have higher NF and smaller bandwidth for C-band operation. This will limit the attainable cost/bit reduction of cladding-pumped MC-EDFAs relative to the baseline case.

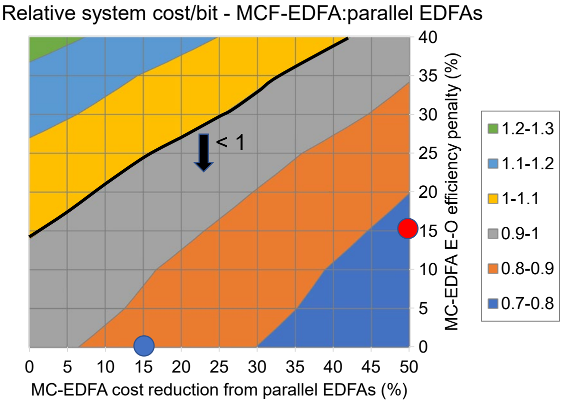

Fig. 1: System cost/bit of systems for MC-EDFAs relative to baseline (parallel SC-EDFAs) for same NF and bandwidth.

Figs. 2 and 3 summarize the modelled cable capacity and relative cost/bit data for the nominal MC-EDFA cases for core-pumping and cladding-pumping. Core-pumped MC-EDFAs can theoretically offer slightly higher cable capacity than parallel SC-EDFAs because they eliminate FIFO losses and FIFO-induced crosstalk, while cladding-pumped MC-EDFAs in both C- and L-bands have reduced capacity because of higher

NF and smaller bandwidth for the C-band system configuration. However, all three MC-EDFAs appear to enable lower system cost/bit compared to the baseline, owing to the lower projected amplifier costs for both types of pumping, as well as the higher core-pumped cable capacity. The cost/bit savings with core-pumped MC-EDFAs could be on the order of 15%.

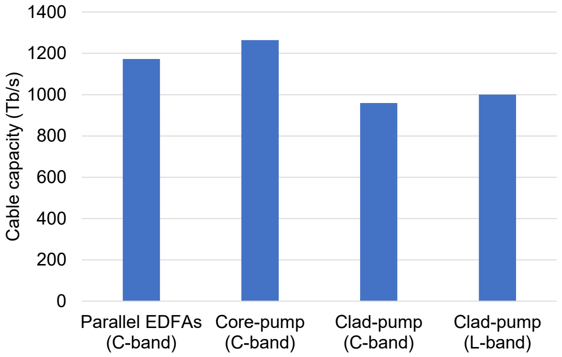

Fig. 2: Cable capacities for different amplifier cases.

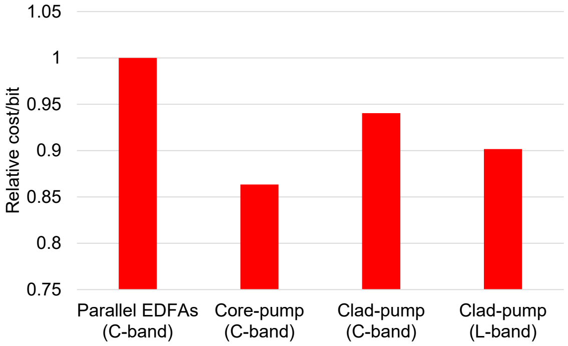

Fig. 3: Relative system cost/bit for different amplifier cases.

While the results in Figs. 2 and 3 correspond to the nominal parameter values for E-O efficiency penalty and MC-EDFA cost reduction, we also investigated the sensitivity of the results to those parameters. The data produced by that study with respect to MC-EDFA E-O efficiency penalty are shown in Figs. 4 and 5 for cable capacity and relative cost/bit, respectively. One result observed is that core-pumped MC-EDFAs could incur an E-O efficiency penalty of up to about 15% and still meet the cable capacity of the baseline case (offsetting the FIFO losses and crosstalk), and also still offer a small advantage in system cost/bit if the nominal cost reduction holds. The cladding-pumped MC-EDFAs could suffer a penalty up to about 20-25% and achieve comparable cost/bit to the baseline although the cable capacities are always smaller due to the higher NF and further decrease with higher E-O efficiency penalty. Fig. 6 illustrates the sensitivity of relative system cost/bit to the actual achieved MC-EDFA cost reduction. Both cladding-pumped amplifier versions need at least 40% cost reduction to enable lower system cost/bit relative to the baseline case. On the other hand, the core-pumped amplifier might still offer lower cost/bit even with a relative cost increase of 10-15%, although our nominal assumption is a decrease of about 15%.

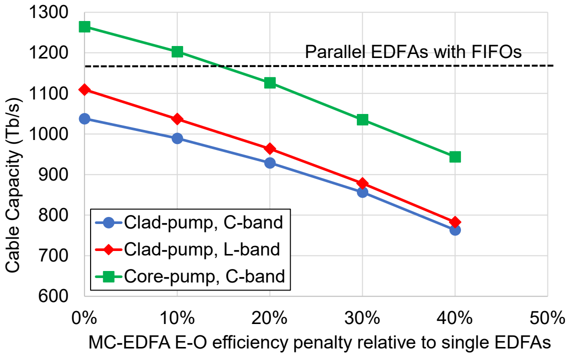

Fig. 4: Cable capacity vs. MC-EDFA E-O eff. penalty.

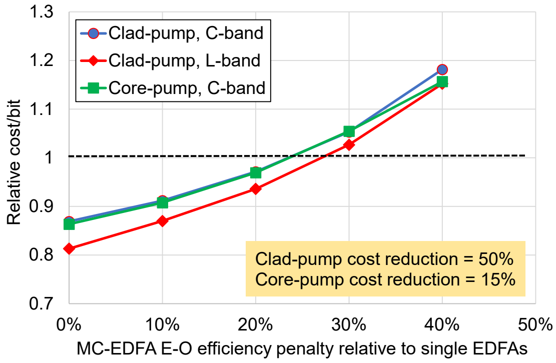

Fig. 5: Relative cost/bit vs. MC-EDFA E-O eff. penalty.

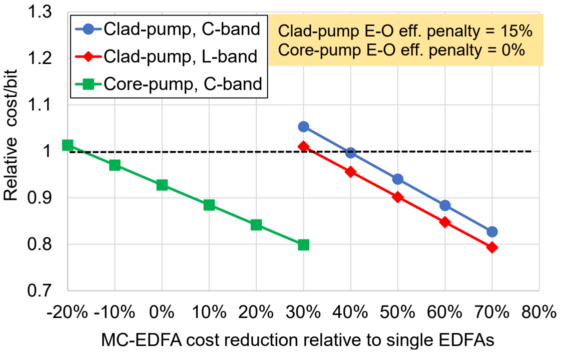

Fig. 6: Relative cost/bit vs. MC-EDFA cost reduction.

Conclusions

We have examined amplification options for MCF submarine systems in the context of attainable cable capacity and relative system cost/bit through modelling. Both core-pumped and cladding-pumped MC-EDFAs may enable lower cost/bit than parallel SC-EDFAs although the reduction is likely small for cladding-pumping because capacity also decreases. Core-pumped MC-EDFAs may provide the best overall long-term solution in both capacity and cost/bit, if MCF components and integration can be practically achieved with minimal E-O efficiency sacrifice.

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