Performance Requirements for FIFO-less Multicore Fibre Repeaters in Transatlantic-class Transmission

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Abstract: We use the extended droop model to evaluate the performance requirements for SDM repeaters in transatlantic systems. The impact of repeater crosstalk on cable capacity is evaluated separately from fibre effects.

1. Introduction

Spatial division multiplexing (SDM) has come forward as a very promising technique for improving the capacity of next generation of long haul cables.The main constraints of long-haul subsea cables are the physical cable diameter and the maximum end power feed. SDM has many technologies but uncoupled multicore fibres (MCFs) have been shown to be favourable as they can fit more cores into the same space. Previous work has shown sharing the power amoung different core can improve the per cable capcaity [1]. MCFs with properties similar to single-core fibre (SCF) have been fabricated [2] and show similar optical qualities to SCF. MCFs can be compatible with current single core technologies after the use of fan in/fan out (FIFO) devices. By using a FIFO device, amplification can be performed with simple single-core EDFAs and the power launched into each core can be easily adapted as needed. However, FIFO devices have inherent loss and crosstalk. These characteristics can detrimentally effect subsea cable performance since hundreds of FIFO devices would be necessary at every single repeater.

To amplify the signal without FIFO devices, multicore EDFAs would be required. For multicore EDFAs, there are two potential schemes, cladding-pumped and core-pumped EDFAs. In a cladding-pumped EDFA, the pump light is confined in the cladding area rather than the core areas and so is only partially absorbed to provide amplification. Although a single pump laser can provide amplification for all cores, pump power cannot be controlled for individual cores. Because of this, core-pumped multicore EDFAs are desirable due to better electro-optic efficiency and individual core gain control.

A FIFO-less design would mitigate the amount of crosstalk but each component of conventional EDFA needs to be replicated as a multicore device. FIFO-less multicore pump combiners, couplers, and Bragg grating based gain flattening filters [3,4] have been demonstrated. In all MCF cases, the isolator is the only component that uses free-space optics and as such contributes towards a source of lumped inter-core crosstalk in the repeater. In this paper, we show the benefits of FIFO-less repeaters in transoceanic systems and the requirements on crosstalk from the constituent components.

2. Simulation method

In order to evaluate capacity per cable we use Shannon's law to calculate the capacity of a given core and then multiply by the number of cores. The SNR is estimated by using the extended droop model. This contains contributions from transceiver noise, ASE, Guided acoustic-wave Brillouin scattering (GAWBS), nonlinear interference noise (NLIN) and intercore crosstalk. These affect the resultant SNR which is then used for the capacity calculations. NLIN is calculated from the EGN model. In a power limited system like that in a subsea cable the end feed voltage is limited. When taking into consideration all the submerged devices a typical maximum feed voltage is 15 kV.

As this is a power limited system we consider the extended droop model [1]. We take the capacity of a fibre to be, $C_{\mathrm{cable}} = 2N_{\mathrm{core}}N_{\mathrm{fp}}N_{\mathrm{ch}}B_{\mathrm{ch}}\log_2(1+\mathrm{SNR})$ where N_{core} is the number of cores in a fibre, N_{fp} is the number of fibre pairs, N_{ch} is the number of channels, B_{ch} is the bandwidth of a channel and SNR is the signal to noise ratio.

In this paper we consider three fibre types, SCF, 2-core fibre and 4-core fibre. A FIFO-less 4 core repeater shown in Fig. 1. Previous research shows that crosstalk and be kept below -80dB/km for both dual and 4 core fibres with a cladding diameter of 125 μm. The parameters are summarised in Table 1. We assume a PFE voltage (V_{PFE}) of 15 kV, 70-GBaud FDP-QPSK signals at a channel spacing of 71 GHz for a total signal bandwidth of 4.2 THz.

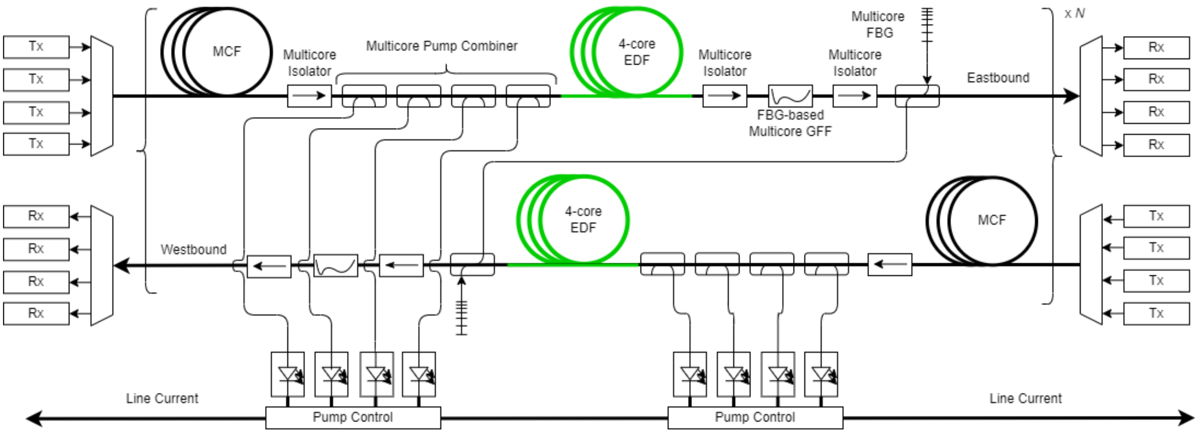

Fig. 1: Setup for a FIFO-less bi-directional four core fibre repeater. Including 4-core Erbium doped fibre (EDF), fibre based couplers, free-space multicore isolators, fibre Bragg grating based multicore gain flatting filters and an optical path for coherent OTDR fault localisation

Table 1: System Parameters, those fixed across systems were transceiver noise 25 dB, EDFA noise figure 5 dB, GAWBS level −60.9 dB/km, 6600 km total length and the same optimisable span length

Parameter	SCF system	2-core system	4-core system
Attenuation [dB/km]	0.154	0.154	0.155
Number of cores	1	2	4
Dispersion [ps/(nm.km)]	21.0	21.6	22.1
Effective area [μm^2]	112	115	87
FIFO loss [dB]	N/A	0.5	
Fibre crosstalk [dB/km]	N/A	−80	−80
Repeater crosstalk [dB/km]	N/A	−60 — −30	

The number of fibre pairs N_{fp} is calculated from,

$$N_{\text{fp}} = \left\lfloor \frac{(1-\varepsilon)\xi V_{\text{PFE}}^2}{8N_{\text{core}}N_{\text{ch}}P_{\text{ch}}L_{\text{sp}}N_{\text{sp}}(N_{\text{ch}}-1)R_0} \right\rfloor \tag{1}$$

where N_{sp} is the number of spans and L_{sp} is the span length which can be changed in order to optimise the number of fibre pairs. The constants ε, ξ and R_0 are control overhead, electro-optical efficient and cable resistance respectively. The values of which are 10%, 1.5% and 1 Ω/km. The SNR is calculated as,

$$\text{SNR} = \frac{P_{\text{sig}}(N_{\text{sp}})}{P_{\text{ASE}} + P_{\text{NLIN}} + P_{\text{GAWBS}} + P_{\text{XTfib}} + P_{\text{XTrep}}} \tag{2}$$

where P_{GAWBS} is calculated for the fibre based on physical constants and effective area [5], which has been experimentally shown to be the same power for MCFs [6]. P_{sig} is the received signal power after droop correction, P_{ASE}, is the amplified spontaneous emission noise, P_{NLIN}, is the nonlinear interference noise, P_{XTfib} is the crosstalk power due to fibre contribution, and P_{XTrep} the crosstalk power from to the repeater. By separating out these contributions we can estimate the level of crosstalk that can be tolerated in a repeater separately from that of the fibre. The system parameters are given in Table 1.

3. Results

We use the model described earlier to calculate the maximum cable capacity from the number of fibre pairs, electrical feed power limit, span length, channel power and SNR. In Fig. 2 we can see the achievable cable capacity plotted as a function of the number of fibre pairs. The maximum achievable capacity for the SCF, 4-core, 4-core FIFO-less, dual-core and dual-core FIFO-less cables are 1.93, 1.53 , 1.93 , 1.54 and 1.90 Pb/s respectively, for more than 40 fibre pairs. By setting an SNR threshold of 6 dB and N_{fp} limit of 24, the cable capacity is limited to 0.76, 0.95, 0.88, 1.16 and 1.15 Pb/s. It can been by introducing the FIFO-less architecture, the MCF cable capacity can be improved by >20% and exceed 1 Pb/s.

On the left hand side of Fig. 3, we can see how the cable capacity relative to SCF changes with repeater crosstalk. At low crosstalk the capacity and number of fibre pairs is maximised and it slowly drops until a step occurs. At a crosstalk of −36 dB the performance of the FIFO SDM system drops below that of the SCF, for FIFO-less this happens at −33 dB.

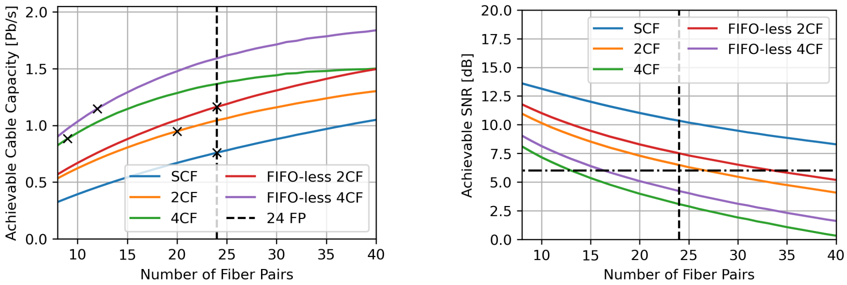

Fig. 2: Left: achievable cable capacity. Right: SNR as a function of the number of fibre pairs at the repeater crosstalk of −60 dB. Cross marks represent maximum capacity under $N_{\mathrm{fp}} \leq 24$ and SNR$\geq$ 6 dB.

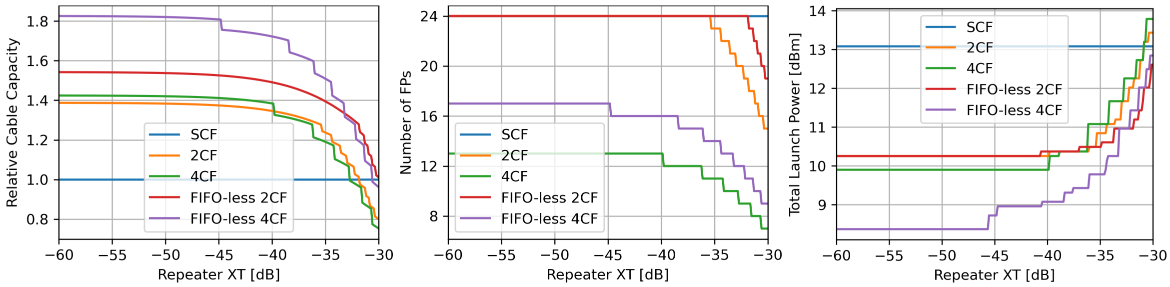

Fig. 3: Left: cable capacity relative to SCF. Middle: number of fibre pairs. Right: total launch power in a single core of all as a function of repeater crosstalk whilst maintaining $N_{\mathrm{fp}} \leq 24$ and SNR$\geq$ 6 dB.

At −53 dB for 2-core and −44 dB for 4-core a step decrease in capacity occurs as the number of fibre pairs is reduced as the SNR drops below 6 dB. FIFO-less amplifiers with < -53 dB have been shown previously [4]. The middle of Fig. 3 shows the number of fibre pairs as a function of repeater crosstalk. Here the discrete drops in capacity can be seen as a drop in number of fibre pairs as the SNR cannot be maintained. On the right hand side we can see how the total launch power per core increases with the repeater crosstalk. As the repeater crosstalk increases, the length of each span is increased such that the total number of repeaters is reduced. For all levels of repeater crosstalk, a FIFO-less system has a higher relative cable capacity. This is due to the excess loss of the FIFO device. It is noted that the maximum cable capacity of a dual-core FIFO-less system is higher than a 4-core system due to the larger effective area and thus incurs less nonlinear penalty.

4. Conclusion

SDM repeaters in long-haul subsea inevitably contribute to intercore crosstalk. Two core fibres are a useful stepping stone to improving cable capacity. We demonstrate that a repeater with a crosstalk level above −53 dB the impact on cable capacity is insignificant. Cable capacity is larger than that of an SCF system until a crosstalk of −36 dB.

Acknowledgements

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