Maximum Submarine Cable Capacity Analysis with C-band, C+L-band, and Multicore Fiber C-band

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Abstract: The maximum capacity of fixed voltage submarine cables is analyzed using single-core fibers with C- and C+L-band systems, and multi-core fibers (MCFs) with C-band transmission. Extra losses for C+L and MCFs limit their relative capacity.
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1. Introduction

Significant research has been devoted in recent years to the area of spatial division multiplexing as a potential technology approach to address growing traffic demands. Most recently, a sharper focus has been placed on the topic of submarine cable capacity in the context of limited electrical power delivery, and how to maximize cable capacity within that constraint [1-7]. In particular, it has been shown that cable capacity can be increased significantly by lowering channel powers and SNR, and increasing spatial multiplicity in the cable [5,7,8]. Another recent study showed minimum cost/bit can be achieved with massive spatial division multiplexing [6]. Increased spatial multiplicity generally implies either increased fiber pair count for conventional single-core fibers or employing multiple cores per fiber or multiple spatial modes per fiber. Another means to increase cable capacity can be to use C+L-band transmission instead of C-band only transmission over conventional single-core fibers, for the same number of fiber pairs.

In this work, we analyze maximum potential submarine cable capacity levels that might be achievable using three different system configurations. These approaches are 1) C-band only transmission over single-core fibers, 2) C+L band transmission over single-core fibers, and 3) C-band only transmission over hypothetical multi-core fibers (MCFs). We follow the general approach of the analysis in [7] and estimate the maximum number of fiber pairs supported for the first two approaches, or pairs of fiber cores in the case of the MCF system. The same target signal-to-noise (SNR) values are evaluated for the three cases. We take into account detailed system losses for the three approaches in order to better estimate the relative maximum cable capacities supported. We find that the extra span losses incurred with both single-core fiber C+L-band transmission and MCF C-band transmission limit their total capacities relative to the baseline case of single-core fiber C-band only transmission. We also observe that for the same cable capacity matched to that achievable with MCFs, both single-core fiber C-band and C+L-band systems may require lower cable voltages than a cable using MCFs.

2. System model

The theoretical maximum cable capacity based on Shannon's theorem can be expressed as

$$C_{cable} = 2N_{FP}N_{ch}B_{sym}\log_2\left[1+SNR\left(P_{ch},L\right)\right] \tag{1}$$

where N_{FP} is the number of fiber pairs, or fiber core pairs in the case of MCFs, N_{ch} is the number of optical channels in each core, and B_{sym} is the symbol rate. The signal SNR is a function of the channel power P_{ch} and the span length L. The relationships that guide the general analysis employed here are based on the optimal electrical current flowing through the cable conductor to power the repeaters [1], an assumption that the SNR regime of interest is high enough to be largely outside the region of "signal droop" [5,8], and the Gaussian noise model of the SNR as a function of channel power and span length for given fiber parameters [9]. We also assume a fixed DC power feed equipment (PFE) voltage V_{PFE} that provides power to the cable. In this approach, the maximum repeater electrical power can be obtained from the assumption of optimal current and minimum voltage (fixed) as

$$P_{rep,max} = \frac{\left(V_{PFE}\right)^2}{4N_{sp}LR_0N_{rep}} \tag{2}$$

where N_{sp} is the number of spans in the link, N_{rep} is the number of repeaters ($N_{rep} = N_{sp} - 1$), and R_0 is the cable resistance. The number of fiber pairs supported as an integer number for a given channel power, span length, electrical-to-optical (E/O) power conversion efficiency η, and repeater control overhead fraction ε, is given as

$$N_{FP} = floor\left[\frac{(1-\varepsilon)\eta P_{rep,\max}}{2N_{ch}P_{ch}}\right]. \tag{3}$$

The cable capacity is evaluated according to Eq. 1 as a function of span length with channel powers set according to the Gaussian noise model to produce a target SNR for the span length, link length, fiber and system parameters.

The fiber and system parameters used in the analysis are shown in Table 1. For C+L-band systems, extra span losses include higher L-band attenuation, higher EDFA noise figure, and C/L bandsplitter losses in the repeaters. For MCF systems, the extra losses include those from fan-in/fan-out (FI/FO) devices [10] in each repeater connecting the MCF cores to individual EDFAs (perhaps a simple and likely implementation at least in the near term), higher intra-span splice losses [11], and assumed slightly higher fiber attenuation. Fiber core parameters in common were 112 μm^2 effective area and 1550 nm dispersion of 21 ps/nm/km. The C-band was 1525-1565 nm and the L-band was 1570-1610 nm. Intra-span splices were spaced every 10 km in the cable.

Table 1: Fiber parameters

Parameter	Single-core C-band	Single-core C+L-band	MCF C-band
Ave. C-band atten. (dB/km)	0.154	0.154	0.158
Ave. L-band atten. (dB/km)		0.156	
C/L bandsplitter loss (dB)		0.5	
MCF fan-in/fan-out loss (dB)			1.0
Intra-span splice loss (dB/splice)	0.02	0.02	0.1

Table 2: System parameters

Parameter	System value
Link length (km)	6,600
Symbol rate (Gbaud)	32
# of channels per band	130
E/O conversion eff. (%)	1.5
Control overhead (%)	10
Cable resistance (W/km)	1
PFE voltage (kV)	15
EDFA NF, C/L (dB)	5.0/5.5

3. Results

An example of the results for a target SNR value at the receiver of 9.5 dB is shown in Fig. 1. Cable capacity data is given in Fig. 1a and the corresponding number of fiber cores supported is given in Fig. 1b. Single-core fibers with C-band only transmission offer the higher cable capacity, but would require up to 37 fiber pairs to carry the maximum capacity. A cable built with MCFs would offer a maximum capacity at about 54% of the single-core fibers and would require 19-20 core pairs. Single-core fibers with C+L transmission could carry ~70% of the capacity of the C-band only fibers, but would require only 13 fiber pairs. In Fig. 1, we show the MCF system data with the attenuation in Table 1 shown with solid red lines, and for comparison, the MCF system data if the fiber attenuation is exactly the same as for single-core fibers with dashed red lines.

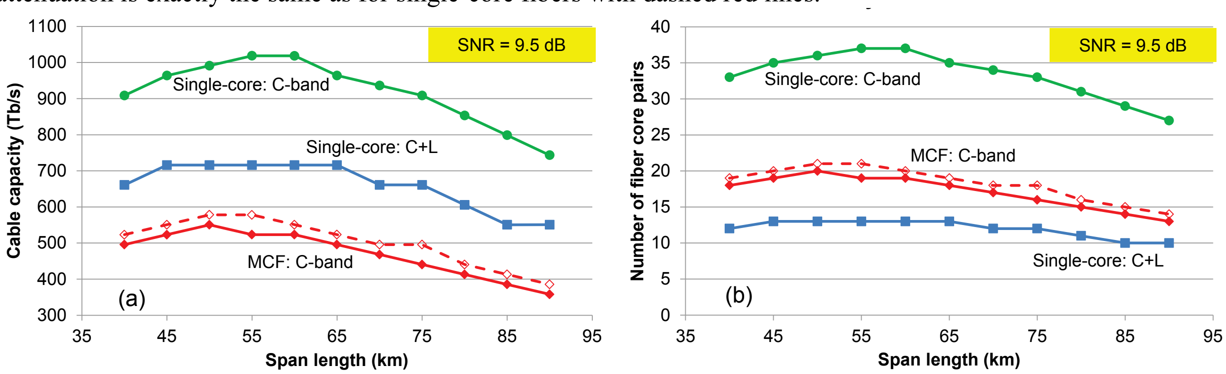

Fig. 1: a) Cable capacity vs. span length. b) Number of fiber core pairs supported vs. span length. SNR target = 9.5 dB.

A summary of the maximum cable capacity results for three different values of target SNR are given in Fig. 2a, with each system type using about the maximum of 15 kV. The SNR values evaluated are in the general range predicted by the minimum cost/bit analysis described in [6]. If all three system types are designed to achieve the same capacity, i.e. the maximum capacity of the MCF system, then the required voltage levels for each system are given in Fig. 2b for 60 km spans. In this case, the single-core fiber C-band and C+L systems require lower cable voltages to deliver the same capacity as the MCF systems by about 25% and 13%, respectively. Given that the largest source of extra loss for the MCF system was the FI/FO devices in the repeaters, we also modeled variations of that device loss as shown in Fig. 3. A reduction of the FI/FO loss to 0.4 dB provides equal MCF system capacity to a C+L system.

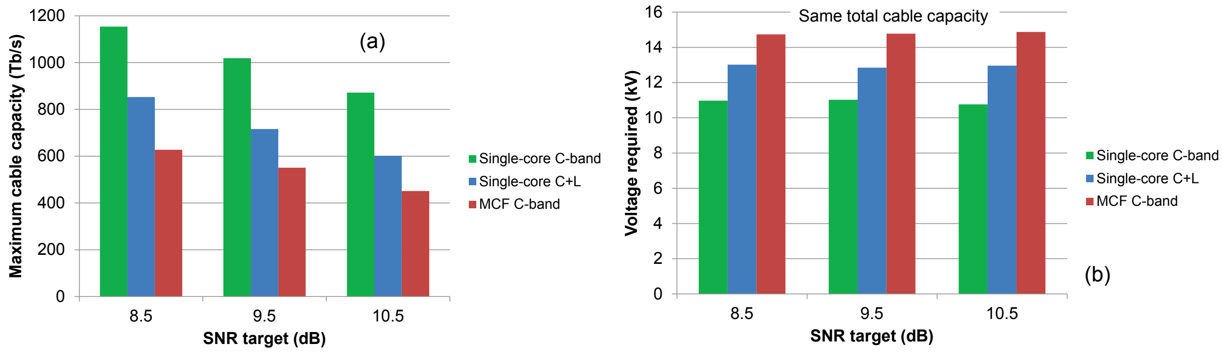

Fig. 2: a) Maximum cable capacity vs. SNR target for voltage up to 15 kV. b) Required voltage with equal cable capacities with 60 km spans for each SNR target value.

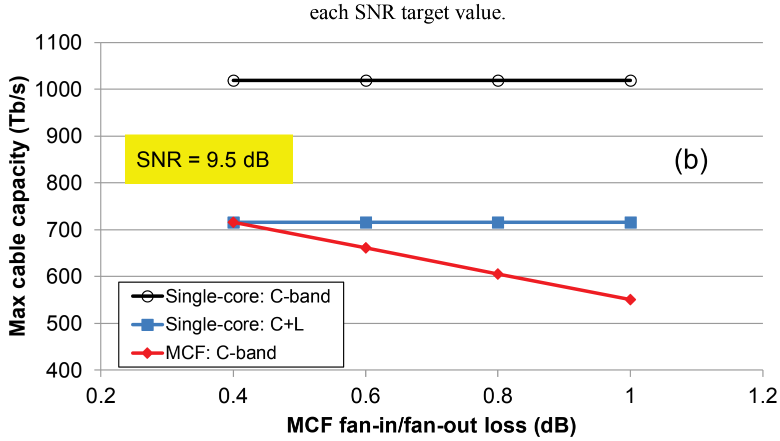

Fig. 3: Maximum cable capacity as a function of MCF fan-in/fan-out loss in repeaters.

While the analysis carried out here has been in the framework of the maximum cable capacity achievable for a target SNR, we note that an alternative analysis can be conducted in the manner of [6] to find the minimum cost/bit. In an initial analysis performed over the same range of SNR targets, we find that the single-core C-band system still has significant capacity advantages, and lower overall cost/bit relative to single-core C+L and MCF C-band systems. More extensive study would be required to investigate outside the SNR range studied here.

4. Summary

We have examined the maximum theoretical submarine cable capacity achievable with single-core and MCF systems with a fixed voltage constraint. Compared to the best case of single-core fibers with C-band transmission, single-core C+L offers about 70% cable capacity, and MCF C-band offers about 54% capacity. If the cable capacities are equalized to the MCF solutions, then the single-core C-band and C+L band systems require about 25% and 13% lower voltage levels, respectively. The reduced total cable capacity levels afforded by C+L or MCF systems are due mainly to extra losses incurred in C/L bandsplitters, and FI/FO devices and splices, respectively.

5. References

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