OPTIMUM FIBER PROPERTIES AND PAIR COUNTS FOR SUBMARINE SPACE DIVISION MULTIPLEXING

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Abstract: It has become increasingly difficult to increase the capacity of a submarine cable by simply increasing the spectral efficiency (SE) over a single fiber pair, due to its logarithmic dependence on the signal-to-noise ratio (SNR). A widely recognized alternative is to use space-division multiplexing (SDM) which increases the number of fiber pairs, resulting in a linear increase in SE. Increasing capacity by adding fiber pairs while cost-reducing the repeater and cable presents a complex optimization problem. In this paper, a techno-economic model based on the Gaussian Noise (GN) model is used to study the optimum fiber pair count and the impact of fiber properties on the cost-per-bit (CPB). Studies include cost and performance tradeoffs from pump-sharing in the amplifiers, limitations on optical launch power from power feed and 980nm pump size, and the resistance per unit length of the cable. Advanced fibers with ultra-low loss, ~0.155 dB/km, exhibit 8-10% capacity and CPB advantage over fibers with ~0.170 dB/km loss in all cases. Furthermore, in spite of launch power limitations, it remains beneficial for capacity and CPB to maintain a larger effective area, *i.e.* to use G.654.B/D fibers, for up to ~24 fiber pairs.

1. INTRODUCTION

The ever-growing global internet traffic, expected to triple over the next five years [1], constantly requires higher capacity optical fiber cables to be deployed over submarine networks. The traditional approach to increasing cable capacity has been to design advanced fibers with lower attenuation and larger effective areas that support higher signal-to-noise ratio (SNR) at the end of trans-oceanic links [2]. Since the corresponding capacity increases logarithmically with SNR, it becomes progressively more challenging to get substantial improvements in the per-fiber capacity [3]. Space-division multiplexing (SDM) was proposed to overcome this limitation by allowing multiple transmission paths, i.e. the capacity of the SDM solution $C_{SDM} = N_{FP} \times C_{SMF}$ where N_{FP} is the number of fiber pairs and C_{SMF} represents the capacity of a single SMF [4], [5].

While SDM increases the cable capacity linearly, it is not without its accompanying trade-offs, particularly in submarine links. Since repeaters in submarine links are powered from the shore, the resulting ohmic losses limit the per-channel signal power, which, in turn, must be shared across all the fiber pairs in the cable [5], [6]. In addition to such a power feed equipment (PFE) constraint, the available per-channel power can be further restricted due to the limited optical power generated by each repeater pump. The problem is further exacerbated when pumps are shared across multiple fiber pairs to reduce repeater costs. As a result of all these effects, the per fiber capacity may decrease as the number of fiber pairs increases.

To maintain the economics of the internet, telecom operators and Web 2.0 companies need to decrease the CPB while supporting increasing traffic rates [5]. The SDM approach increases cable capacity, but it is not clear *a priori* if it lowers the cost per bit. This techno-economic optimization problem was first discussed in [5], [7], and the PFE constraint was considered in that effort. This paper reports studies of the cost and performance tradeoffs from limitations on optical launch power due to pump-sharing in the amplifiers, the 980 nm pump size, and two different cable resistivities, in addition to the PFE constraint.

The GN model [8] is used to estimate the cable capacity under these launch power constraints while realistic fiber and amplifier cost models are used to evaluate the CPB for both trans-Pacific and trans-Atlantic submarine links. We compare fibers with lower attenuation and/or larger effective area against a baseline 80 μm^2, ~0.170dB/km fiber, which has been in the market for almost 20 years, showing that advanced fibers have better cost vs. performance trade-offs for SDM. Since the optimum CPB varies little over a fairly broad range of fiber counts, the model suggests employing ~20-25 fiber pairs to achieve low CPB, in most scenarios, while limiting wet plant costs. It is found that in this regime, a high-performance fiber with effective area 125 μm^2, loss 0.155 dB/km fiber can realize ~8-10% wet plant CPB savings while providing ~12% capacity increase compared to the lower cost baseline fiber.

A significant factor that is not readily amenable to modeling is the maximum number of fibers, of a particular effective area that can be practically cabled in a given cable design, without suffering noticeable excess attenuation from attendant micro- and macrobending sensitivities. Because such attenuation scales with effective area, from general principles, one may assume that a larger number of small effective area fibers can be packaged into the same cable design, compared to a larger effective area fiber design. However, this topic remains to be fully explored. It is believed that fibers with 125$\mu m^2$and even 150 μm^2can be cabled in existing, cost-effective cable designs up to 12 and 16 fiber pairs today without undue degradation of optical attenuation. It is possible that future cable designs for 24 fiber pairs will accommodate 125 μm^2 fiber designs as well.

2. FRAMEWORK FOR CAPACITY AND COST-PER-BIT MODELING

The GN model is used to analyze the capacity of uncompensated submarine links with coherent detection. The capacity (in one direction) with N_{FP} fiber pairs and total spectrum W is given by:

$$C_{SDM} = 2N_{FP}W \log_2 \left[1 + \frac{SNR}{\rho}\right] \quad (1)$$

$$SNR = \frac{P_{SIG}}{P_{ASE}+P_{NLI}} \quad (2)$$

where SNR is the signal-to-noise ratio at the end of the link and ρ is the SNR distance from Shannon capacity including any transceiver implementation penalties. A past generation of coherent modem corresponds to an SNR gap of $\approx$7dB whereas a 4dB margin may better approximate the performance of modem in the near future. While the GN model can be used to estimate the ASE noise power P_{ASE} and nonlinear interference (NLI) noise power P_{NLI} at the end of the link, an additional modification is required to properly mimic the behavior of amplifier cascades in submarine links [9]. Since submarine repeaters are typically operated in the constant total output power regime, eventually the signal power degrades as it shares the gain medium with the growing ASE noise. This "signal droop" [10] and its impact on the signal and ASE can be modeled using the approach outlined in [9]. However, since the corresponding NLI power evolution was not addressed in [9], we have separately analyzed it [11] and have used it to estimate capacity in this paper. It should be noted that the ASE and NLI power depend on the number of spans N_s, number of channels, N_{ch}, baud rate R_{sym}, fiber attenuation α, chromatic dispersion D, effective area A_{eff} and the nonlinear coefficient n_2.

The power feed equipment (PFE) imposes an upper bound on the per-channel launch power given by [5-7]:

$$P_{ch} \leq \frac{\eta_{EO} V_{PFE}^2}{8 R_{PFE}} \cdot \frac{L_{sp}}{L_{link}^2} \cdot \frac{1}{N_{ch} N_{FP}} \quad (3)$$

where V_{PFE} is the PFE voltage, R_{PFE} is the resistance of the cable (per unit length), η_{EO} is the electrical to optical power conversion efficiency, L_{sp} is the span length and L_{link} is the desired reach of the submarine system. The PFE parameters are usually cable specific and typically vary depending on whether the link is trans-Pacific ($R_{PFE} = 1\,\Omega/\text{km}, \eta_{EO} = 3.5\%$) or trans-Atlantic ($R_{PFE} = 1.3\,\Omega/\text{km}, \eta_{EO} = 2\%$). While this work uses a PFE voltage of 15 kV, there is discussion in the industry that 18kV-20 kV or even higher PFE voltages may be eventually realized.

The 980 nm pump power limitation translates into the maximum output power that the EDFA can support (= 20 dBm here). The PFE and EDFA power parameters used in this paper have been arrived at after careful calibration against known commercial submarine cable deployments. It should be pointed out newer cable designs, including using aluminum instead of copper as the power conductor, are likely to correspond to a different set of PFE/EDFA parameters.

Pump sharing reduces cost by dividing the available 980 nm pump power across EDFAs serving two or more fiber pairs. Indeed, some suggest that pump sharing is a pre-requisite for true SDM. In this paper, we use the nomenclature “*PS-n*” to denote sharing two pumps across n fiber pairs. For example, the maximum per channel power for a 20 dBm output power EDFA with *PS-1* is 2.4 dBm, with *PS-2* is -0.65 dBm and with *PS-3* is -2.4 dBm. We have assumed full C-band operation with 75 GBaud signaling rate and Nyquist pulse shaping.

The CPB estimates used in this paper largely follow the framework of [5], [7]. The wet plant cost c_{WP} is given by:

$$c_{WP} = L_{link}\left[c_D + c_C + 2N_{FP}c_F + \frac{c_A}{L_{sp}}\left(\frac{2N_{FP}}{n}\right)\right] \quad (4)$$

where c_D, c_C, c_F, c_A are the costs related to deployment, cable, fiber, and amplifier respectively. The cable cost c_C is inversely proportional to the cable resistance, R_{PFE}. The amplifier cost c_A is estimated based on its components and accounts for pump sharing. Table 1 provides an estimate of some these costs normalized to the cost of a 100G transponder, where the choice of cost reference does not impact the results.

Item	Normalized Cost
Deployment cost c_D (per km)	0.7
Cable cost c_c (per km)	0.24 – 0.48 (resistance based)
Repeater cost c_A	1.2 – 2.3 (pump sharing based)
Fiber cost c_F (per km)	0.0014 – 0.004
100G transponder	1.0

Table 1: Normalized costs

Note that when the fiber pair count is extremely large, newer, larger cables will be required with larger core tubes and lower resistivities. The accompanying cable cost increase is not factored into the current analysis.

The wet plant cost per bit is obtained by taking the ratio of the wet plant cost c_{WP} and the cable capacity (in both directions = $2C_{SDM}$).

3. SPAN LENGTH OPTIMIZATION

To understand the performance of a given fiber type, the number of fiber pairs in the cable and the span length are swept while monitoring various metrics such as cable capacity, wet plant cost and wet plant cost per bit. For example when a $125\mu m^2$, 0.155 dB/km fiber in a trans-Pacific link (represented here by 11,000 km reach) is considered, the contours of launch power, spectral efficiency, capacity and wet plant CPB are as shown in Figure 1.

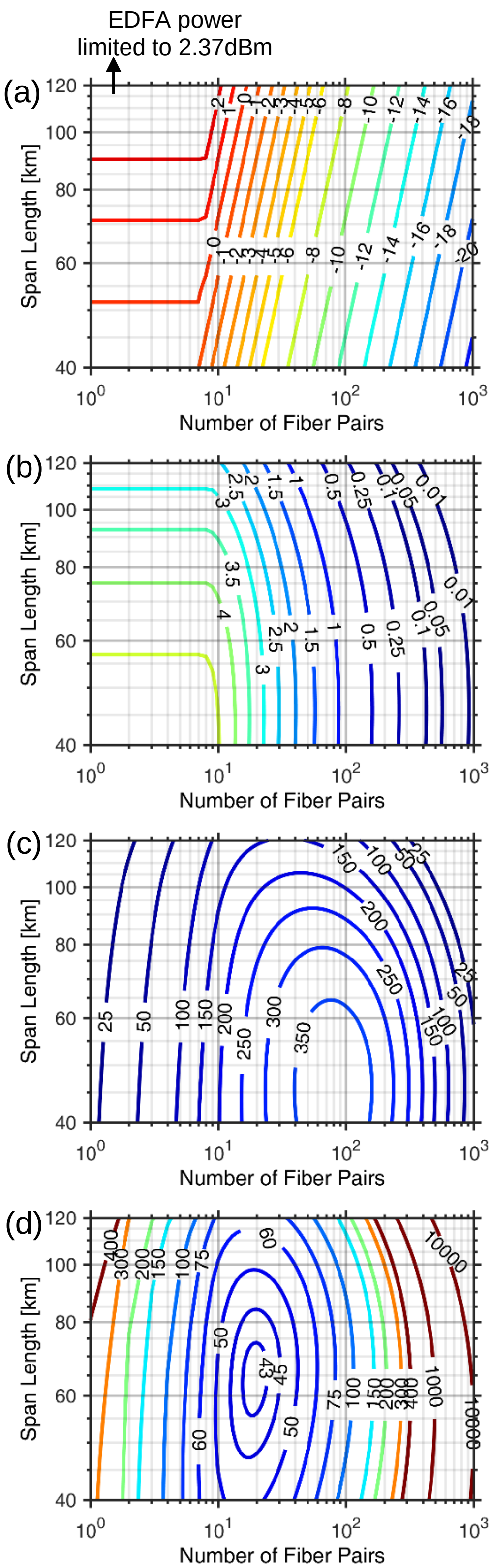

Figure 1: Trans-Pacific (11,000 km) link performance for the 125μm^2, 0.155 dB/km fiber with *PS-1* at 7 dB from Shannon Capacity (a) launch power per channel in dBm (b) spectral efficiency in bps/Hz (c) cable capacity in Tbps (d) normalized wet plant CPB.

The per-channel launch power P_{ch} can be in one of three regimes, Fig.1a. For less than 8 fiber pairs, the P_{ch} contours are horizontal and are determined by the balance between the ASE noise power and the NLI noise power. When the spans are extremely long, the EDFA pump power limitation and pump sharing can limit the launch power to 2.37 dBm (here). As mentioned earlier, with *PS-2* and *PS-3*, the launch power is limited to -0.65 dBm and -2.4 dBm respectively. Beyond 8 fiber pairs, the launch power is limited by the PFE ohmic losses as indicated by the positively-sloped straight line contours in Fig.1a. In the PFE limited regime, the spectral efficiency contours are curved and fall-off with increasing number of fiber pairs, Fig.1b. This rapid fall-off, particularly with extremely large number of fiber pairs, is due to the “signal droop” phenomenon described earlier. Therefore, the cable capacity contours have an optimum around 100 fiber pairs, Fig. 1c. However, the normalized wet plant CPB contours have an optimum around ~20 fiber pairs and ~65 km spans. Going forward, for each fiber pair count, the span length that minimizes the normalized wet plant CPB is chosen.

4. ADVANCED FIBERS

To understand the impact of fiber properties on submarine link performance, the techno-economics of large effective area G.654.B/D fibers such as 125μm^2 (*e.g.* OFS TeraWave® SCUBA 125 fiber) and 150μm^2 (*e.g.* OFS TeraWave® SCUBA 150 fiber) fibers, both with 0.155 dB/km attenuation, are compared to an 80 μm^2 fiber with 0.170 dB/km attenuation (such as the well-known G.654.C “Z-fiber”) as the baseline case. Lower attenuation versions of an 80 μm^2 fiber (0.165 dB/km, 0.160 dB/km and

0.155 dB/km) are evaluated. Reasonable assumptions about relative fiber costs are made based on fabrication costs, production volumes, specifications, and competitive forces. Using the approach of the previous section, the performance of different fibers are compared in Figs. 2 & 3.

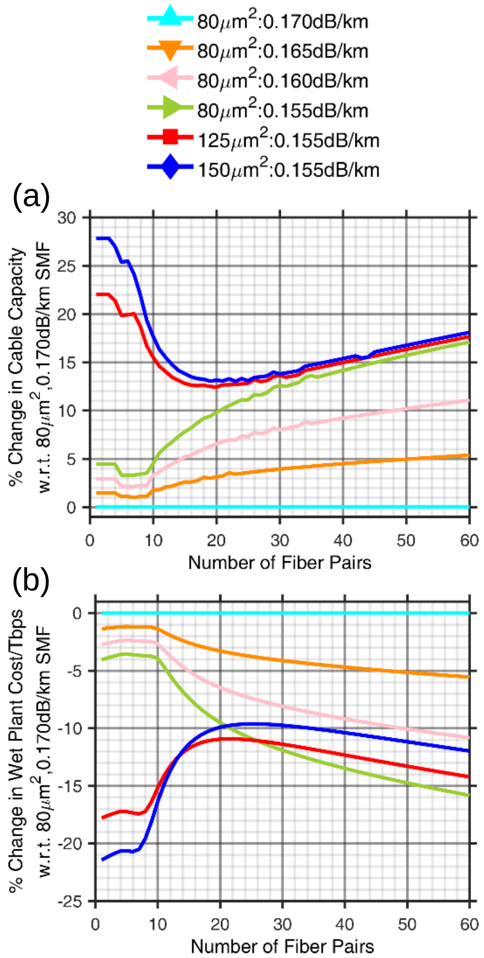

Figure 2: Advanced fibers compared to $80\mu m^2$,0.170 dB/km fiber over a 11,000 km Trans-Pacific link with *PS-1* at 4 dB from Shannon Capacity (a) % Change in capacity (b) % Change in wet plant CPB.

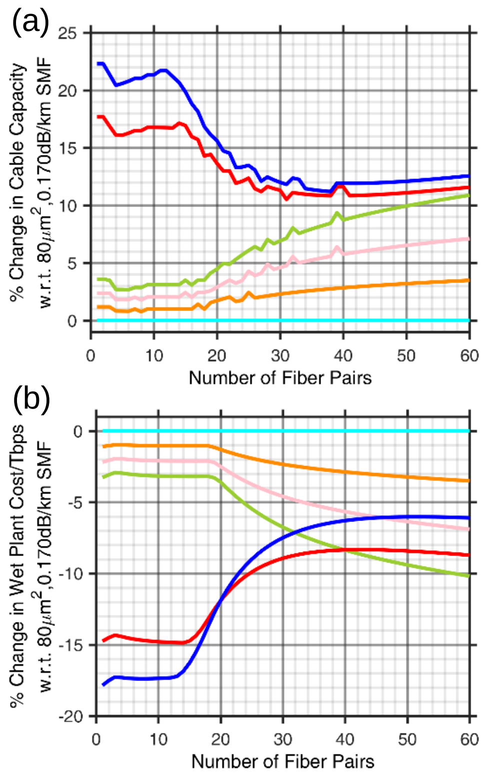

Figure 3: Advanced fibers compared to $80\mu m^2$, 0.170 dB/km fiber over a 5,500 km Trans-Atlantic link with PS-1 at 4 dB from Shannon Capacity (a) % Change in capacity (b) % Change in wet plant CPB.

Clearly, all the advanced fibers – both the larger effective area fibers and /or the lowest attenuation fibers have better techno-economics than the baseline 80 μm^2 , 0.170 dB/km fiber. Furthermore, there are two regimes of operation across all fibers. In the low fiber count case, which we shall call the *non-SDM regime*, the ultra-low loss fibers with larger effective area have higher capacity and lower cost per bit compared to the $80\mu m^2$ fibers. On the other hand, in the *SDM regime* the fibers with lowest attenuation perform better. This can be understood by going back to the launch power picture, Fig. 1a. In the SDM regime, the launch power is limited due to the PFE constraints resulting in the fibers being used in their linear regime. Consequently, the fiber attenuation determines performance in the SDM regime. In the non-SDM regime, either the fiber nonlinearity or the EDFA power limitation is operational. Since these launch powers are closer to the nonlinearity-limited launch optimum launch powers of these fibers, the fibers with larger effective areas result in less nonlinearity and hence higher capacity and lower CPB.

Based on the above results, we infer the following regimes where advanced fibers are to be preferred as a function of fiber count, assuming that suitable cable designs are available.

	$150\mu m^2$ **0.155dB/km**	**$125\mu m^2$** **0.155dB/km**	**$80\mu m^2$** **0.155dB/km**
Trans-Pacific	< 10	10-24	> 24
Trans-Atlantic	< 16	16-32	> 32

Table 2: Fiber Pair count regimes where different advanced fibers are preferred (at 4 dB from Shannon Capacity).

Note that the above fiber pair regimes do not change much when we switch from *PS-1* to *PS-2* to *PS-3* – the main reason being that pump sharing only impacts the performance in the non-SDM regime. Considering all three pump sharing scenarios (*PS-1* to *PS-3*), the $125\mu m^2$, 0.155 dB/km fiber with 20-25 fiber pairs has ~8-10% lower wet plant CPB and ~12% higher capacity than the $80\mu m^2$, 0.170 dB/km fiber for both trans-Pacific and trans-Atlantic links.

5. OPTIMIZING NUMBER OF FIBER PAIRS

Thus far, the span length that minimizes the CPB was chosen while comparing fibers. In this section the fiber pair count is chosen to optimize the wet plant CPB. In the case of the trans-Pacific link with *PS-3* at 4 dB SNR from Shannon Capacity, the optimum number of fiber pairs is 27-30, Fig. 4. However, the CPB curve, Fig. 4b, indicates that the most dramatic reduction in cost per bit occurs in going from ~8FPs to ~20FPs with diminishing returns beyond that. A more prudent approach is to utilize ~20-25FPs to take advantage of the CPB reduction while limiting the absolute wet plant cost. Significantly, Fig. 4a shows that limitations in optical and electrical power begin to limit capacity growth vs. fiber pair, with the slope decreasing around 12 fiber pairs and again above 24 fiber pairs. This indicates that subsequent generations of SDM with increasing fiber counts will give diminishing returns unless the electrical power available is increased through cable re-design.

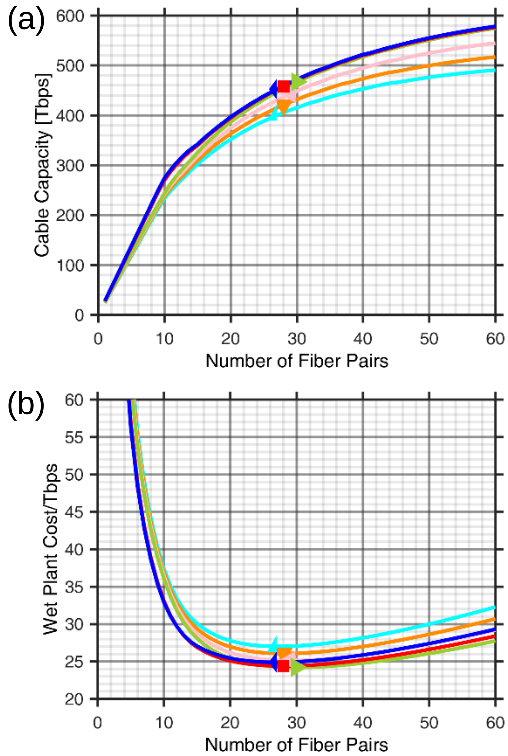

Figure 4: Advanced fibers compared to $80\mu m^2$, 0.170 dB/km fiber over a 11,000 km Trans-Pacific link with *PS-3* at 4 dB from Shannon Capacity (a) cable capacity (b) normalized wet plant cost per Tbps.

In the case of the trans-Atlantic link with *PS-3* at 4 dB from Shannon Capacity, the optimum number of fiber pairs increases to 45-50, Fig. 5. Since the cost per bit curve is flatter compared to even the trans-Pacific case, once again, most of the CPB benefit can be realized by utilizing 20-25FPs while

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limiting the wet plant cost. Again, the capacity growth becomes flatter in Fig. 5a after about 24 fiber pairs. This reinforces the idea that ~24 fiber pairs is the near-term optimum at current power feed limits. But it also indicates that an increase in voltage will be required to maintain the benefits of SDM over more than one or two generations.

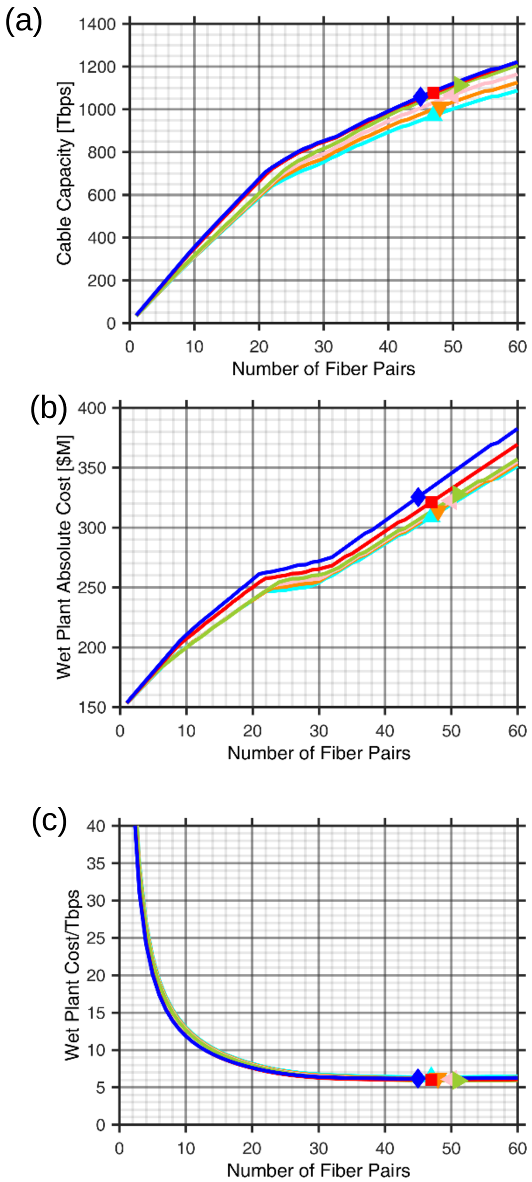

Figure 5: Advanced fibers compared to $80\mu m^2$, 0.170 dB/km fiber over a 5,500 km Trans-Atlantic link with PS-3 and a 4 dB SNR margin (a) cable capacity (b) normalized wet plant cost per Tbps.

6. CONCLUSIONS

A techno-economic model has been discussed which balances the cost and performance of SDM submarine cable systems considering variables such as fiber pair count, span length, fiber specifications, amplifier pump sharing and pump size, and cable conductor resistivity. Due to the relatively flat nature of the cost per bit curves near the optimum, we recommend utilizing ~24 fiber pairs to achieve lower CPB while limiting the absolute wet plant cost. Different advanced fibers have been compared for SDM against an 80 μm^2 , 0.170 dB/km baseline fiber from a wet plant CPB perspective. The model shows that large effective area fibers with ultra-low loss provide techno-economic benefit up to 20-25 fiber pairs. At the point where cable packing density requires a lower effective area design, then the fibers with lowest possible attenuation give the best CPB.

Specifically, the model predicts that a 150 μm^2 0.155 dB/km fiber (*e.g.* the TeraWave SCUBA 150 fiber) optimizes techno-economic value up to 10 FPs (16FPs) for the trans-Pacific (trans-Atlantic) links, respectively. Fiber counts from 10FPs-24FPs (16FPs-32FPs), favor a 125 μm^2 , 0.155 dB/km fiber (*e.g.* the TeraWave SCUBA 125 fiber), while beyond these intervals, the lowest attenuation fiber that can be cabled without excessive loss would be most beneficial. Near the cost-performance optimum of 20-25 fiber pairs, the 125 μm^2 ,0.155 dB/km fiber has ~8-10% lower cost per bit and ~12% higher capacity compared to the baseline 80 μm^2 , 0.170 dB/km fiber thereby underscoring the techno-economic value of advanced fibers. New cable designs for future SDM to enable higher power feed voltage and higher fiber counts should also aim to accommodate larger effective area, ultra-low loss fibers.

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