Techno-Economics of Terrestrial Extensions of Subsea Routes

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Abstract: This paper investigates the benefit of using ultra-low-loss G.654.E fiber in the terrestrial section of PoP-PoP route in terms of GSNR improvement, higher fiber pair and cable capacity, and increased system value.

1. Introduction

Space Division Multiplexing (SDM) has become the de-facto design for most repeatered subsea systems being built today, and further advances in SDM to reduce cost per bit are currently being explored [1]. In parallel, in many networks regeneration is being removed at the subsea-terrestrial interface to create a longer end-to-end route. Such an approach is frequently referred to as "PoP-PoP" - it allows for an elimination of expensive regenerators and enables the termination of data traffic directly in a terrestrial data center. In some cases, extending subsea routes terrestrially are geographically necessary. An example is connecting Africa, Asia and Europe over Telecom Egypt's terrestrial crossing routes to the Red Sea in the East and the Mediterranean Sea in the West. This makes trans-Egypt crossings a convenient and cost-effective way to route Africa-Asia-Europe data traffic.

In this work, we quantify the extent to which an ultra-low-loss and large effective area (A_{eff}) fiber in the terrestrial section of the PoP-PoP route can preserve high-value subsea data traffic. This paper expands previously published work [2,3] to include most recent subsea SDM design principles and to show an improvement in terms of fiber pair (FP) capacity (in Tb/s), cable capacity (in Tb/s) and total system value (in $M). Our analysis is carried out over a wide range of subsea and terrestrial lengths, thereby capturing most practical use cases. This includes lengths representing typical terrestrial crossings across Egypt.

2. Methodology

We first model the transmission performance separately for a terrestrial and subsea route by calculating Generalized Signal-to-Noise Ratio (GSNR) for each section using a Gaussian-noise model, and then estimate the combined link GSNR using the equation: $1/GSNR_{TOTAL} = 1/GSNR_{SUBSEA} + 1/GSNR_{TERRESTRIAL}$ [3]. We assume that the combined link consists of one optically amplified terrestrial and one repeatered subsea section but note that some deployments may contain multiple terrestrial and subsea sections. For the subsea section, we use a moderately large (115 μm^2) effective area fiber, representative of submarine fiber suitable for SDM and non-SDM systems. For the terrestrial section, we compare the performance of three fibers: legacy G.655, ultra-low-loss G.654.E, and best-in-class G.652.D (Table 1). Legacy G.655 fiber loss of 0.25 dB/km was chosen to represent fiber attenuation available at the time and reflects field splices introduced as a result of cable cuts and repairs that might have accumulated over ~20-year cable operation. We also note the choice of cable design for new deployments may affect fiber attenuation.

Table 1. Summary of key fiber attributes used in the transmission performance modelling [2]

	Legacy G.655 (Terrestrial)	G.652.D (Terrestrial)	G.654.E (Terrestrial)	115 μm^2 fiber (Subsea)
Loss (dB/km)	0.250	0.183	0.166	0.150
Dispersion (ps/nm/km)	4	17	21	20
Effective Area (μm^2)	72	80	125	115
Nonlinear refractive index x 10^{-20} (m^2/W)	2.3	2.3	2.2	2.1

To avoid nonlinear interference overestimation for short G.655 fiber sections we applied a modulation-dependent corrected term, as described in [4]. In terrestrial sections we assumed Erbium-only amplification with 5 dB noise figure and fixed transmission spans of 100 km, while for subsea sections we used lower noise figure of 4.5 dB and variable repeater spacing, according to methodology described in [5]. We also used 1.5 – 2.5 dB difference between the actual launch power and the nonlinear optimum power [5]. The SDM design rules used in this work are summarized in Table 2, which also assumed 95 Gbaud transmission with 46 wavelengths. For the terrestrial section we used a nonlinear optimum launch power into the fiber that yields highest GSNR, given that transmission over terrestrial sections is not subject to electrical power constraints. We included the impact of Guided Acoustic Wave Brillouin Scattering (GAWBS) in both terrestrial and subsea transmission, and the impact of signal droop in subsea transmission only [2]. We also used 0.02 – 0.2 dB splice loss within and at the endpoints of each terrestrial span, depending on the A_{eff} of two spliced fiber types. For the terrestrial spans we also used 4 dB end-of-life cable margin to account for future cable repairs – this was applied to all terrestrial fiber studied in this work to ensure the same level of network reliability. Finally, all cable sections were assumed to be 6 km, and 0.5 dB loss per connector was applied.

Table 2. Repeater spacing and fiber launch powers for submarine SDM transmission

Route Length (Mm)	5	6	7	8	9	10	11	12	13	14	15
Repeater spacing (km)	100	100	100	100	95	90	90	90	85	85	85
Launch power differ. vs. NL (dB)	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	2.5	2.5
Actual launch power (dBm)	2.0	2.0	2.0	2.0	1.7	1.0	1.0	0.9	0.7	0.2	0.2
Typical # of fiber pairs (FPs)	24	23	22	20	19	18	17	16	14	13	12

We then converted GSNR into channel capacity using the equation: 2 x Baud Rate x $\mathrm{Log}_2(1+\mathrm{GSNR}/2)$. Here the factor of 2 in the denominator reflects modem imperfections (3dB gap-to-Shannon), which makes channel capacities more relatable to real-world deployments. To convert channel capacity into FP capacity and cable capacity, we multiply this by the number of wavelengths and then by the number of FPs in the subsea cable, respectively. We assume that a typical subsea system could operate with 24 FPs at 5,000 km and 12 FPs at 15,000 km, and the numbers of FPs at intermediate distances are calculated using a linear interpolation, rounded to the nearest integer number (Table 2).

3. Results and Discussion

Fig. 1 shows the difference in PoP-PoP fiber pair capacity gain when using G.654.E vs. G.652.D fiber (Fig. 1a) and G.654.E vs. G.655 fiber (Fig. 1b) terrestrially, based on GSNR calculation methodology as described earlier. The range of GSNR values for all modelled scenarios was between 4.95 and 12.33 dB.

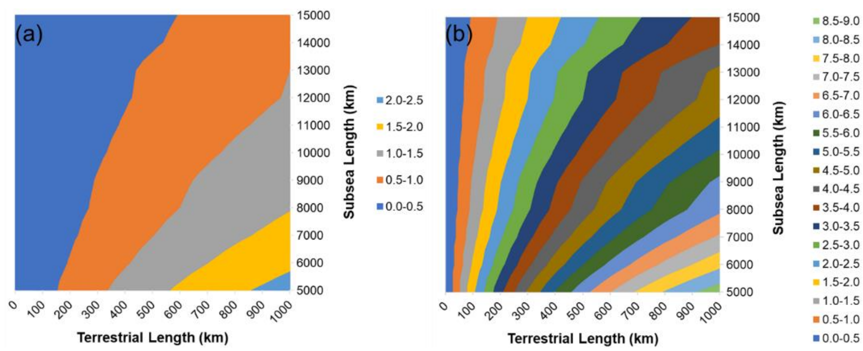

Fig. 1. Capacity per FP gain (Tb/s). (a) G.654.E vs. G.652.D ; (b) G.654.E vs. G.655

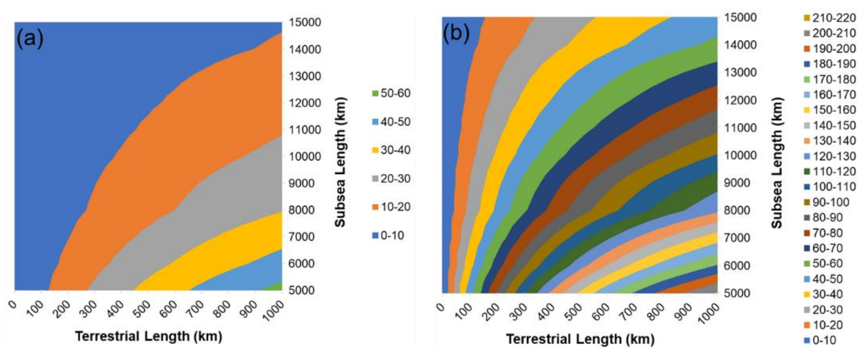

Fig. 2. Capacity per cable gain (Tb/s). (a) G.654.E vs. G.652.D ; (b) G.654.E vs. G.655

The contours were chosen such that each color change corresponds to 0.5 Tb/s FP capacity gain. The comparison of Fig. 1a and 1b shows the extent to which the use of legacy G.655 fiber is detrimental in terms of total FP capacity for a PoP-PoP route. We find that the use of ultra-low-loss G.654.E fiber provides up to 2.2 Tb/s per FP capacity gain over G.652.D fiber, and up to 8.8 Tb/s per FP capacity gain over G.655 fiber. The gain is larger for longer terrestrial and shorter subsea lengths due to the higher relative contribution of a terrestrial fiber on PoP-PoP transmission performance. When capacity gain per FP is converted into cable capacity gain (Fig. 2), the contours become flatter due to the different number of FPs assigned to a cable as a function of distance. The use of G.654.E fiber provides up to 53 Tb/s higher cable capacity vs. G.652.D fiber, and up to 212 Tb/s higher cable capacity vs. legacy G.655 fiber.

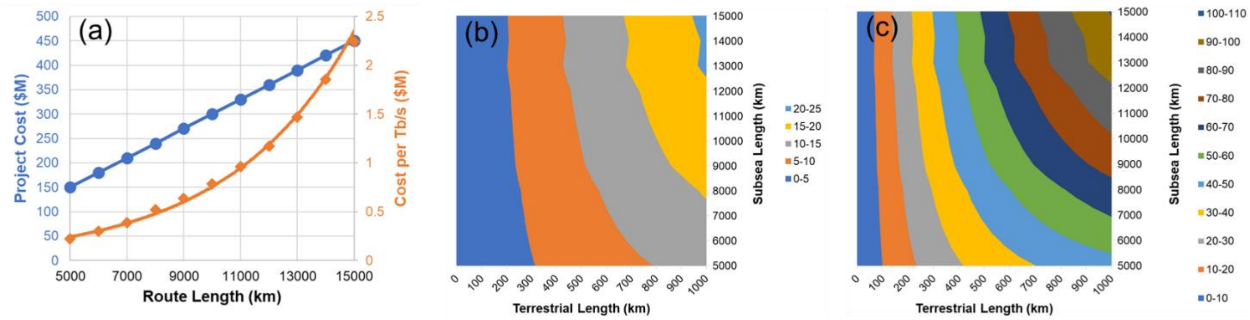

Fig. 3. (a) Estimated project cost and cost per Tb/s as a function of subsea route length; (b) System value gain ($M) for G.654.E vs. G.652.D terrestrially; (c) System value gain ($M) for G.654.E vs. G.655 terrestrially

To study the techno-economics of using G.654.E vs. G.652.D / G.655 fibers in a terrestrial section, we used a $30,000/km subsea route construction cost [6], and assumed that construction cost would scale linearly with route length (Fig. 3a). While the true cost of subsea routes is inherently difficult to estimate due to project-to-project variabilities related to number of branches, deployment conditions and other cost components, we believe our approach is reasonable in the context of this techno-economic study. We also modeled the cost per Tb/s by dividing project cost by cable capacity values from Fig. 2 based on the assumed number of FPs with subsea length in the scenario where terrestrial length is set to zero. Fig. 3b and 3c show the total system value enabled by ultra-low-loss G.654.E associated with subsea capacity preservation. The results demonstrate that the use of an ultra-low-loss G.654.E fiber provides a significant additional system value: up to $21M when comparing against G.652.D fiber (Fig. 3b), and up to $101M when comparing against legacy G.655 fiber (Fig. 3c). These additional system values are significantly higher than an incremental cost of new fiber deployment compared to re-using legacy routes, although this aspect was not studied in detail in this work. We also observed that the additional system value enabled by G.654.E fiber is more pronounced for longer subsea routes, largely because of higher capacity unit value for longer subsea routes (as previously shown in Fig. 3a).

4. Summary

This paper presents a new way of looking at the value of advanced terrestrial fibers – from the traditional view to reduce number of amplifier sites to an emerging value of subsea cable capacity preservation. We show that ultra-low-loss G.654.E fiber in the terrestrial section of the PoP-PoP route can provide significant improvement in end-to-end cable capacity and system value. We demonstrate that G.654.E fiber can provide up to 53 Tb/s higher cable capacity compared to G.652.D fiber, and up to 212 Tb/s higher cable capacity compared to legacy G.655 fiber. When converted to system value, these differential cable capacities translate to system values up to $21M and $101M, respectively. This work highlights the importance of using ultra-low-loss G.654.E fiber to carry high-value subsea data traffic for terrestrial extensions of subsea routes, particularly for trans-Egypt, Africa-Asia-Europe diverse crossings.

5. References

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