Investigation of Fiber Parameters for Subsea Systems with Terrestrial Backhaul

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Abstract *The choice of terrestrial fiber is found to have a significant impact on transmission performance. The SNR advantage enabled by newer, ultra-low-loss fibers compared to legacy G.655 fibers is determined to be as high as 4.5 dB, although substantial transmission scenario dependent variabilities are observed.*

Introduction

The past few years have seen significant changes in how submarine systems are designed, with space division multiplexing (SDM) emerging as the de-facto approach for enabling high-capacity cables with lower cost per bit[1]. To achieve that, the SDM philosophy relies on using more fibers per cable, in which each fiber operates at a launch power that is lower than in traditional non-SDM systems[2],[3].

In parallel, many submarine SDM routes designed today provision for signal regeneration to be moved away from the landing station into the terrestrial point-of-presence (PoP), thus increasing the total unregenerated route length[4]. Despite the emergence of PoP-PoP links, the impact of various fiber combinations in this configuration has remained largely unstudied. To the best of our knowledge, this is the first comprehensive investigation of fiber type impact on the transmission performance of subsea links with terrestrial extension.

Methodology

The schematic diagram used as a basis for our analysis is shown in Fig. 1, in which we assume a symmetric submarine link extension on both ends of the ocean. To model the transmission performance of such a link, we used the Gaussian-noise (GN) model[5],[6] to calculate electrical signal-to-noise ratio (SNR) separately for submarine and terrestrial sections. The total link SNR is then calculated using Eq. (1):

$$\frac{1}{SNR_{TOTAL}} = \frac{1}{SNR_{SUB}} + \frac{2}{SNR_{TER}} \tag{1}$$

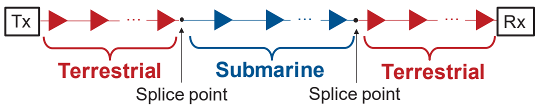


Fig. 1: Schematic diagram

For the terrestrial segments of the route, we modelled SNR of four fibers with parameters shown in Tab. 1. G.655 fiber was chosen to represent the legacy fiber that was deployed in large volumes in the late 1990s[7], and still available today to route terrestrial data traffic in some places. We also assumed an elevated level of G.655 fiber attenuation to reflect higher attenuation specification limits that were prevelent at this time as well as field splices introduced as a result of cable cuts and repairs that might have accumulated over the ~20-year cable operation. To compensate for nonlinear interference overestimation for short G.655 fiber routes, we applied a modulation-dependent correction term[8], which allowed for a reduction in the discrepancy between Monte Carlo and GN simulations from 0.7 dB to 0.2 dB. For the three new fibers we used different attenuation values, representing regular and ultra-low-loss (ULL) fibers, different nonlinear index of refraction (IOR), and different effective area (A_{eff}) grades for optical fibers commonly available in the market today. We varied the length of the terrestrial

Tab. 1: Parameters of fibers under study for terrestrial portion of the route

	Legacy G.655	80µm^2 regular	80µm^2 ULL	G.654.E ULL
Loss (dB/km)	0.250	0.195	0.158	0.168
Dispersion (ps/nm/km)	4	17	17	21
Effective area (µm^2)	72	80	80	125
Nonlinear IOR x 10^{-20} (m^2/W)	2.3	2.3	2.1	2.2
Raman gain coefficient (1/W/km)	0.53	0.40	0.34	0.24
Loss at Raman pump λ (dB/km)	0.30	0.23	0.21	0.22

Tab. 2: Repeater spacing and launch power for submarine SDM transmission

Route length (Mm)	5	6	7	8	9	10	11	12	13	14	15
Repeater spacing (km)	100	100	100	95	95	90	90	85	85	85	80
Launch power vs. NL optimum (dB)	-1.5	-1.5	-1.5	-1.5	-1.5	-2	-2	-2	-2.5	-2.5	-2.5

section with a step of 100 km and studied both EDFA-only and Raman-assisted transmission. The terrestrial system EDFA noise figure was set to be 5 dB. For backward-pumped Raman assisted transmission we assumed that 12 dB EDFA gain will be required to maintain a 5 dB EDFA NF, with the rest of the span loss amplification provided by Raman pump power.

For the submarine section, we studied two fiber options: 80 μm² A_{eff} with 0.158 dB/km attenuation, and 115 μm² A_{eff} with 0.150 dB/km attenuation. We also looked at a wide range of distances from 5 Mm to 15 Mm to capture three main route categories: transatlantic, transpacific, and ultra-long transpacific. The amplifier spacing and launch powers (Tab. 2) were set based on the methodology described in[9] for a hypothetical 300 Tb/s cable capacity, which we assumed to be also true for fibers with A_{eff} of 80 μm² and 115 μm². We also included the impact of a generalized signal droop model for an accurate SNR estimation at low launch powers[10],[11]. This accounts for span-by-span power transfer between signal and noise in the presence of constant output power amplifiers. The submarine EDFA NF was set to be 4.5 dB (0.5 dB lower than for terrestrial EDFA NF).

At the terrestrial-submarine interface we used different splice losses (0.02-0.2 dB) depending on the A_{eff} of two spliced fiber types. For both terrestrial and submarine transmission modelling we included the impact of Guided Acoustic Wave Brillouin Scattering (GAWBS), according to the methodology previously described in[12],[13]. We observed that there was a significant (0.3-0.5 dB) SNR reduction when including GAWBS, and the impact was particularly pronounced for longer routes. For the active equipment we assumed 64 x 70 Gbaud PM-QPSK channels, spaced at 75 GHz without implementation penalty.

Results and Discussion

Fig. 2 shows contour graphs that represent the difference in SNR for PoP-PoP routes that utilised the same submarine fiber (0.150 dB/km with 115 μm² A_{eff}) but different fibers (Tab. 1) in the terrestrial section. As such, the SNR difference in Fig. 2 is defined as SNR of the PoP-PoP route containing a new terrestrial fiber minus the SNR of the PoP-PoP route based on legacy terrestrial G.655 fiber. For ultra-long submarine routes with short terrestrial extensions, the transmission performance is largely dominated by the submarine fiber, and thus the impact of terrestrial fiber type was found to be less pronounced. Conversely, the performance of terrestrial fiber becomes more impactful for shorter submarine routes with long terrestrial extensions. It is also apparent that the transition from G.655 to regular G.652 fiber (Fig. 2a) yields up to 3.2 dB improvement in SNR due to significant differences in attenuation and dispersion. The transition to the next-grade, 80 μm² ULL fiber (Fig. 2b) provides further noticeable SNR gain of up 1 dB depending on the transmission scenario. Finally, the transition to ULL G.654.E fiber (Fig. 2c) provides a further but modest (up to 0.25 dB) SNR gain compared to 80 μm² ULL fiber. This leads to the conclusion that 80 μm² ULL and G.654.E ULL fibers have comparable merit from a transmission performance standpoint, and the decision to deploy one versus another should be also driven by other considerations (e.g. availability in different cable designs). We have also repeated

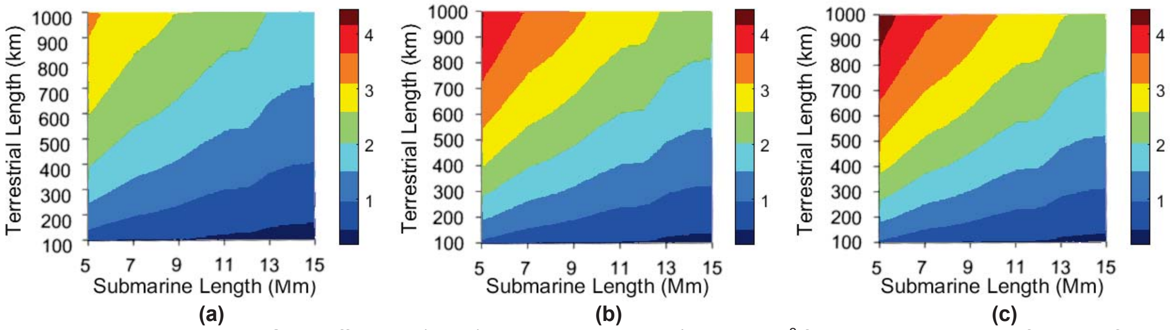
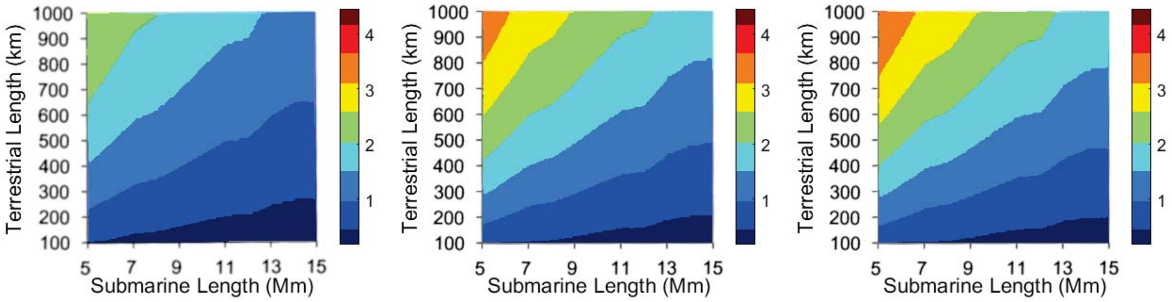


Fig. 2: Total PoP-PoP link SNR difference (in dB), assuming 0.150 dB/km, 115μm² fiber in subsea and the following fiber pairs in the terrestrial sections (a) 80μm² regular vs. G.655 (b) 80μm² ULL vs. G.655 (c) G.654.E ULL vs. G.655

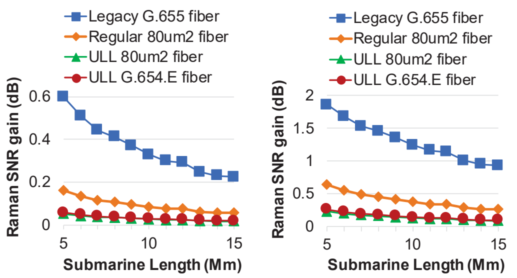


(a) **(b)** **(c)**

Fig. 3: Total PoP-PoP link SNR difference (in dB), assuming 0.158 dB/km, 80 μm^2 fiber in subsea and the following fiber pairs in the terrestrial sections (a) 80 μm^2 regular vs. G.655 (b) 80 μm^2 ULL vs. G.655 (c) G.654.E ULL vs. G.655

this modelling using a 0.158 dB/km, 80 μm^2 fiber in the subsea route (Fig. 3). While the overall shapes of the contours follow a similar trend compared to Fig. 2, we observed a smaller SNR difference for the same pairs of terrestrial fibers. This is because the additional noise from the terrestrial sections has a bigger impact with 0.150 dB/km, 115 μm^2 fiber due to its higher overall SNR compared to 0.158 dB/km, 80 μm^2 fiber.

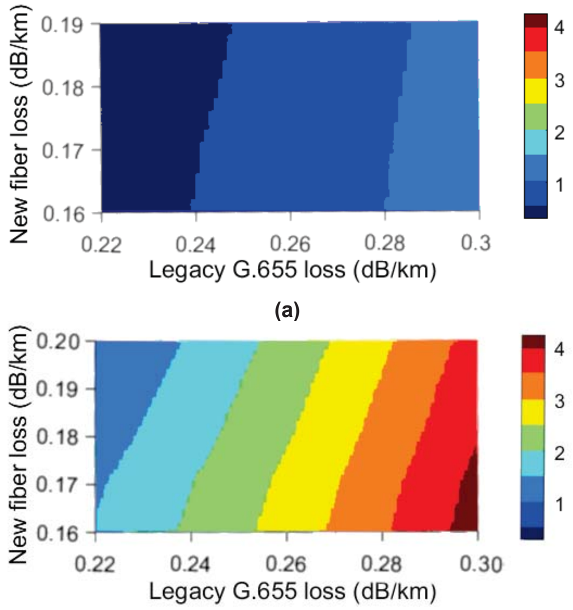
We then studied the SNR gain that could be achieved when using Raman vs. EDFA-only amplification in the scenarios with 100 and 500 km terrestrial section lengths (Fig. 4a and 4b, respectively). Fig. 4 shows that Raman amplifier yields higher SNR gain for a legacy G.655 fiber, making it a worthwhile technology to partially offset the additional span losses incurred throughout the 20-year cable operation. Conversely, for newer fibers with lower attenuation the use of Raman amplification provides a lower (<0.6 dB) performance benefit compared to EDFA-only terrestrial systems. The required Raman pump power was found to be within 0.5 W for all fibers under test.



(a) (b)

Fig. 4: SNR gain attributed to using Raman-assisted vs. EDFA-only transmission for a route with (a) 100 km terrestrial length; (b) 500 km terrestrial length

Finally, we performed a sensitivity analysis to study the relative importance of different attenuation levels for both new 80 μm^2 and legacy G.655 fibers. Here we fixed subsea route length to 7,000 km to represent transatlantic-like distances, containing 0.150 dB/km, 115 μm^2 fiber. The importance of lower attenuation for new fiber was found to be significantly more pronounced for routes with longer terrestrial extensions, represented by more distinct contour slopes of 500 km (Fig. 5b) compared to 100 km (Fig. 5a) transmission. The SNR advantage of new fiber increases further when compared against lossier G.655 fiber cable spans.



(b)

Fig. 5: Total PoP-PoP link SNR difference (in dB), assuming 0.150 dB/km 115 μm^2 fiber in a 7,000km subsea link with (a) 100 km terrestrial length; (b) 500 km terrestrial length

Conclusions

This paper investigated several transmission scenarios to determine the impact of terrestrial fiber parameters on PoP-PoP subsea transmission. A significant variability in SNR gain enabled by modern, ultra-low loss fiber versus legacy G.655 fiber was observed across different scenarios. This work highlights the need for lower attenuation specifications for the new fiber to create significant transmission performance improvement compared to legacy G.655 fibers.

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