TECHNO-ECONOMIC STUDY OF OPTICAL LINKS CONTAINING BOTH SUBMARINE AND TERRESTRIAL SEGMENTS

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Abstract: With the advent of "open systems" in the submarine optical communication space, there has been increasing interest in flexibility on the location of the terminal equipment. Networks are now being conceived with terrestrial and submarine segments which are fully integrated (and optimized) without regeneration. As more terrestrial distance is added to highly-engineered submarine links, concern arises with the penalties incurred by the quality of the terrestrial components (optical fiber and EDFA amplifier). It is shown here that the integrated approach of selecting optimal span lengths and fiber types is beneficial to obtaining the lowest cost-per-bit in mixed terrestrial/submarine systems. The GNI model is used to compute link performance as a function of fiber type and EDFA noise figure over different combinations of terrestrial and submarine reach. Significant cost savings (~ 20%) are obtained by using ultra large area (G.654.B/D) ultra-low attenuation (ULL) in the ocean segments of the link. Additional savings (~ 8% with 2000 km terrestrial segments) obtain from optimized spans of large effective area fiber (G.654.E) with ULL properties in the terrestrial segments compared to the use of standard G.652.D fiber.

1. BACKGROUND

A confluence of business and technology factors are driving a need for flexibility in the location of terminal equipment in submarine links [1]. Where certain shore locations have historically provided landing/colocation points for an ocean cable system, there is now interest in blended ocean/terrestrial systems with minimal regeneration [2, 3], with landing points at more convenient/cheaper locations, which are often some distance from the shoreline. The coherent transmission technologies are quite similar in the two segments (ocean and terrestrial) and with open cables, often the same system integrators offer products for each type of network [4].

To most effectively design the blended link, it is best to optimize both the submarine and terrestrial link segments simultaneously. This is possible in the case of a greenfield installation, where one can closely mimic the performance of the ocean fiber in the terrestrial system. If some, or all, of the terrestrial segments are already in place, then the optimization problem is constrained by those segments chosen for re-use. The substantial cost of a submarine deployment is such that consideration should be given to improving the (possibly weak) performance of the terrestrial link segments.

Though there are many different cost trade-offs to be made in designing such a mixed network, the focus here is on the applicability of advanced optical fibers to the various segments in the link. Historically, submarine and terrestrial networks have used different fiber types because of environmental, craft and cost constraints. This may be less justified in cases where a submarine link is compromised by a poorly performing terrestrial segment. In addition, the impact of high noise figure terrestrial amplifiers is examined. Finally, cost estimations are made of using G.652 fiber in the ocean segment. These issues will be addressed by considering several different fiber types in mixed links < 10,000 km where it is assumed that submarine segment lengths/fiber counts are low enough that electrical power restrictions do not apply. This restriction can be easily relaxed later by imposing a further constraint on the optimization.

The two properties of modern fibers which are most important for long distance transmission are attenuation and optical mode field diameter (or equivalently mode effective area) [5]. Low attenuation preserves the signal through the link with lower required amplification. Amplifiers generate noise, so the less gain required from them, the cleaner the transmission. Because the optical fiber core is so small, the light is confined in a very small cross-sectional area. Over long transmission distances tiny nonlinear interactions between the light and the glass fiber add up to problems. This is alleviated by spreading the light over a larger core size. The largest mode field diameter submarine fibers today use a cross-sectional area nearly twice that of standard single mode fibers. This allows more optical power to be launched into the fiber without hitting the nonlinear limits.

A metric now commonly used to value network design options is the "cost-per-bit" ratio or CPB. This is a ratio of the total costs: deployment, cable, optical fiber, repeaters etc. to the aggregate capacity (in terabits-per-second) of all the fibers in the cable when fully lit. So, any time one component is considered for upgrade, a calculation can be made to verify that this new component will provide enough added capacity to justify its additional cost. It is shown here that for cables with 8 – 12 fiber pairs, CPB savings of up to 20% can be obtained by using ultra-low-loss (ULL), ultra large effective area (ULA) optical fibers (in the ITU categories G.654.B, D or E) as opposed to conventionally sized G.652 ULL or generic G.652.D optical fibers. Examples will be shown here using OFS's TeraWave® fibers in mixed terrestrial/submarine links.

After outlining the method of analysis, a description is given of optimizing span length to minimize CPB for a wide range of mixed link segment reaches. Then comparison is made between fiber types on a single-fiber type 7,500 km link, where the CPB sensitivity to span length choice is computed. A mixed fiber case follows, which describes trade-offs in total cost, capacity and CPB. Finally, the CPB impact of upgrading terrestrial segment fiber to G.654.E is shown.

2. MEASURING LINK PERFORMANCE

Figure 1 shows a sample link, connecting two data centers, which includes both terrestrial and submarine segments. Possible fiber choices to use in these segments are listed in Table 1. Other parameters to consider in link optimization includes span length and impact of amplifier noise figure, (only EDFA

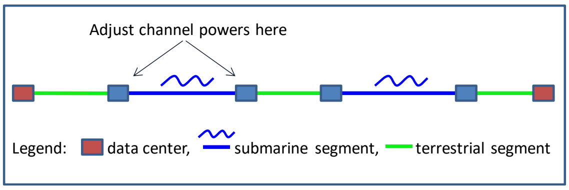

Figure 1: Data center connection using both submarine and terrestrial segments.

ITU Fiber Type (with OFS product)	Usage	Atten. (dB/km)	Effective Area (μm^2)
G.652.D (AllWave® LL)	Terr.	low (0.184)	standard (83)
G.652 ULL	Terr./ Subm.	lower (0.170)	standard (82)
G.654.E (TeraWave® ULL)	Terr.	lower (0.170)	large (125)
G.654.B/D (TeraWave® SCUBA125)	Subm.	Ultra-low (0.155)	large (125)
G.654.D (TeraWave® SCUBA150)	Subm.	Ultra-low (0.154)	large (153)

Table 1: Applicable fiber types and their typical properties/uses.

reported here). Nonlinear index of G.652.D fiber is 5.4% greater than the other fibers in Table 1.

The transmission performance is computed using the Gaussian Noise Interference Model (GNI) in its LOGON approximation (Nyquist, WDM channels) [6]. Though not applicable to every link, this model gives good results for links employing today's coherent technology over long distances. Using this tool, the link optical signal-to-noise-ratio (OSNR) can be estimated quite accurately, even in the nonlinear regime (where optical channel powers are high). The electrical signal-to-noise-ratio (SNR) is obtained at the end of the link, after conversion from the optical to electrical domain, and includes all noise sources, whether from repeaters or fiber nonlinearity.

In lieu of specifying a particular transmission scheme (modulation format, operating margin etc.) it is assumed that the system operates within 6 dB of the Shannon limit. Therefore, the total noise in the computation is increased by 6 dB from the raw GNI results and the derated SNR is used in the Shannon Equation to compute spectral efficiency, SE, (dual polarization is assumed). Cable transmission capacity, C, is found from SE by multiplying by the optical bandwidth (C-band operation gives $B_{C\text{-band}} \sim 4$ THz) and the number of fibers, N_f :

$$C = 2 \cdot \log_2(1 + SNR) \cdot B_{C\text{-band}} \cdot N_f \qquad (1)$$

3. MEASURING LINK COST

The cost model used here is based on the submarine model of [7] with some modifications for the terrestrial segments. These modifications include: cheaper, noisier optical amplifiers, a wide range of deployment costs (urban vs. rural), cost of huts (greenfield), and inclusion of splice losses (splices every 6 km instead of every 50 – 60 km in submarine). The cost for each segment can be summarized:

$$c_{seg} = (c_d + c_c + c_f N_f) \cdot L_{seg} + c_a \cdot N_s \cdot N_f + c_t \cdot C \qquad (2)$$

where c_{seg} is the cost for the link segment under consideration, c_d, c_c and c_f are the costs-per-km of deployment, cable and fiber, respectively; N_s is the number of spans, L_{seg} is the segment length, c_t is the transponder cost (normalized to the cost of a 100 Gbps transponder) and C is the total capacity of the link in Gbps. Terrestrial segments may include hut cost: $c_h \cdot N_s$. The total link cost is the sum of the costs for each segment (ocean and terrestrial). Table 2 shows the normalized costs used in this work. Equation (2) divided by Eq. (1) yields the CPB.

Item	Cost (norm.)
Submarine deployment (per km)	0.7
Submarine cable (per km)	0.5
Terrestrial deployment (per km)	0.33
Terrestrial cable (per km)	0.052
Submarine repeater	2.0
Terrestrial repeater	0.25
Fiber (type dependent, (per km)	0.00032 to 0.005
Terrestrial hut	19.0
100 Gbps transponder	1.0

Table 2: Normalized cost breakdown

4. OPTIMUM SINGLE SEGMENT LINKS

Before generalizing to links with segments having different properties, it is useful to briefly review the case of a link with uniform properties throughout. The GNI model finds the channel power which optimizes the OSNR at link end to be the same at that which optimizes OSNR at the end of each span. Hence calculations can be performed on a per-span basis (which makes the analysis of mixed links straightforward). Figure 2 shows a sketch of the trade-offs in minimizing CPB with span length. The link performance degrades as the span increases because of the increased repeater gain required to overcome the excess fiber/splice loss. Hence the SE (red curve) drops with increasing span length. At short span lengths costs, due to the increasing frequency of repeaters, explode (black curve). The span length which balances these two phenomena optimizes the CPB (near 100 km in Figure 2). Increasing the repeater NF in this link will lower and steepen the SE curve, impairing performance at longer span lengths. This causes the optimum span length to decrease.

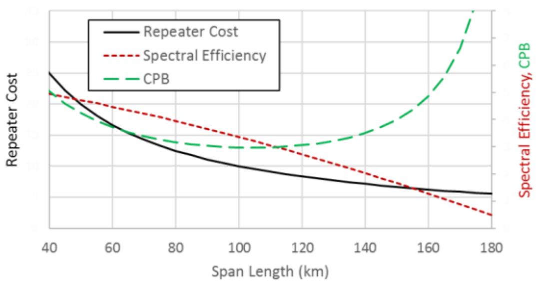

Figure 2: Minimizing Cost-per-bit (CPB)

Dividing Eq. (2) by (1) shows that the scaling of CPB with N_f is:

$$CPB = d_1/N_f + d_2$$

so that the CPB drops as more fibers are added to the cable (this assumes no change in cable or deployment costs). Here d_1 depends on deployment, cable and hut costs while d_2 depends on fiber, repeater and transponder costs. For typical link parameters $d_1/d_2 \sim 25$ so the fiber count must be quite high (~ 25) for the fiber dependence of CPB to weaken.

It is to be noted that link optimization may be subject to other constraints than CPB, such as the overall system cost or capacity. Another constraint will occur in brownfield terrestrial segments where the span lengths cannot be freely chosen due to existing infrastructure. In this case the existing 60 – 100 km hut spacing must be utilized.

5. OPTIMUM MIXED LINK DESIGN

In practice there can be any number of segments of each type interspersed in an arbitrary way throughout the link. Fortunately, in the GNI model, optimum link optical performance is obtained when the OSNR of each span length is individually optimized. So the segment order does not matter and if all the submarine segments have the same properties, they can be treated as one long segment with $OSNR_{ocean} = OSNR_{s,ocean} / N_{s,ocean}$. The same is true for the terrestrial segments and the link OSNR given by:

$$1/OSNR_{link} = 1/OSNR_{ocean} + 1/OSNR_{terr}$$

Of course, if not all spans/segments of a given type have the same properties, they must be explicitly added. For simplicity, the cases described here have one set of identical properties for submarine spans and another set of identical properties for the terrestrial spans. Optimization will typically lead to different channel powers in the two segments. Additionally, for the remainder of the paper, the submarine NF = 4.5 dB.

One of the key choices to make in designing mixed links is the span length in each segment. Typically, the CPB-optimized span length is shorter in the terrestrial segment than the ocean segment because of the extra losses (splices), higher EDFA NF (cheaper amplifiers) and lower performing fiber of the terrestrial segment. Figure 3 shows optimum span length for all combinations of segment reach up to 10,000 km for a G.652.D (terrestrial) / SCUBA 150 (ocean) link. The NF = 6 dB for the terrestrial segment. Primarily because of the large difference in fiber performance and submarine repeater costs, the optimum span length in the ocean segment is nearly twice that of the terrestrial. Note that the origin of this plot is (500 km, 500 km), so all the span length curves converge toward the actual origin (0 km, 0 km). At higher terrestrial NF, the optimum terrestrial span lengths become even shorter.

To drill into some detail on optimum span lengths, an example is now shown for mixed

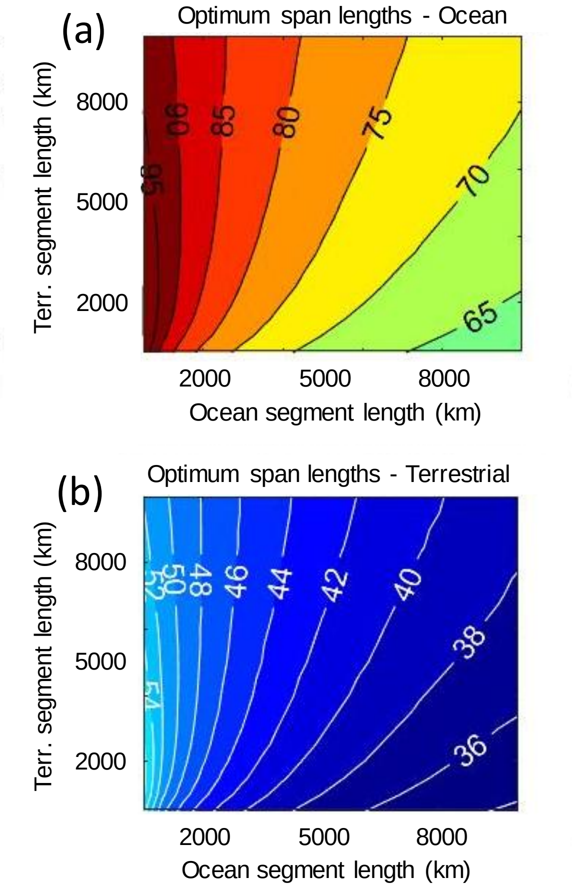

Figure 3. Optimum span lengths for (a) ocean and (b) terrestrial, with G.652.D fiber in terrestrial segment (NF = 6 dB) and TeraWave® SCUBA 150 in ocean.

links containing a single fiber type. Figure 4 shows the CPB (normalized dollars per terabit-per-second) in level contours for a 7,500 km link (6,000 km ocean, 1,500 km terrestrial) using three different fiber choices in a 24-fiber cable with terrestrial NF = 6 dB. Use of the same fiber type throughout the link emphasizes the added performance of the large effective area submarine fibers (SCUBA 125 and SCUBA 150) as well as the terrestrial/submarine performance trade-off.

The circular contours in Fig. 4 show the existence of a clear CPB minimum, around a terrestrial span length of 40 – 50 km and an ocean span length of 60 – 70 km. This minimum occurs because in both segments of the link cost increases with short span lengths (too many expensive repeaters) and capacity decreases with increasing span length (SNR starts eroding due to the excess noise from the EDFA amplifiers). The SCUBA fibers allow a longer optimum spacing between ocean repeaters, thereby delivering cost savings. It is also seen that terrestrial span lengths can be increased with the SCUBA fiber. The result is nearly a 20% cost savings when using SCUBA 125 throughout the link rather than G.652 ULL fiber. Finally, note that the CPB minimum in the SCUBA case is shallower than that of the standard fiber case. This indicates that deviances from optimum span lengths (such as having to work with pre-existing spans in brownfield terrestrial segments) will not be as expensive when using SCUBA fibers.

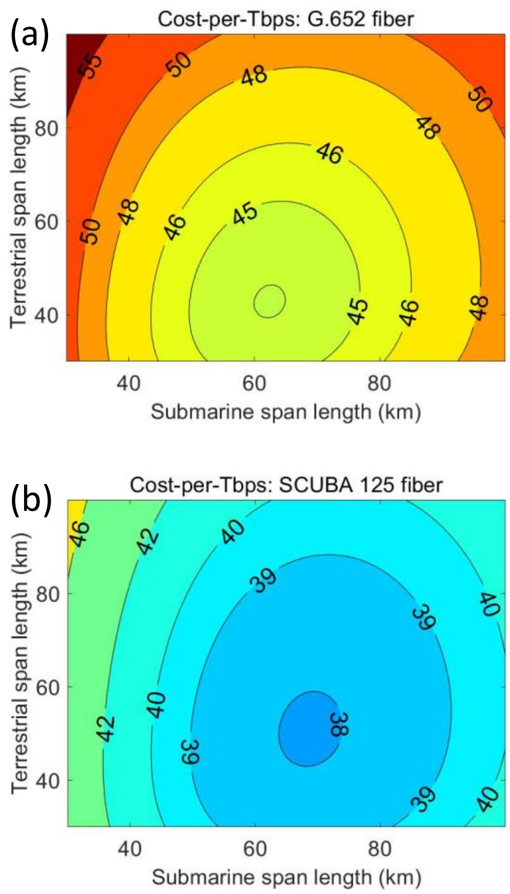

Figure 4. Normalized cost per Tbps in a 7,500 km link using different fibers: (a) G.652 ULL (ocean) with G.652 fiber (terrestrial), and (b) TeraWave SCUBA 125 throughout. Red indicates high cost, blue, low cost.

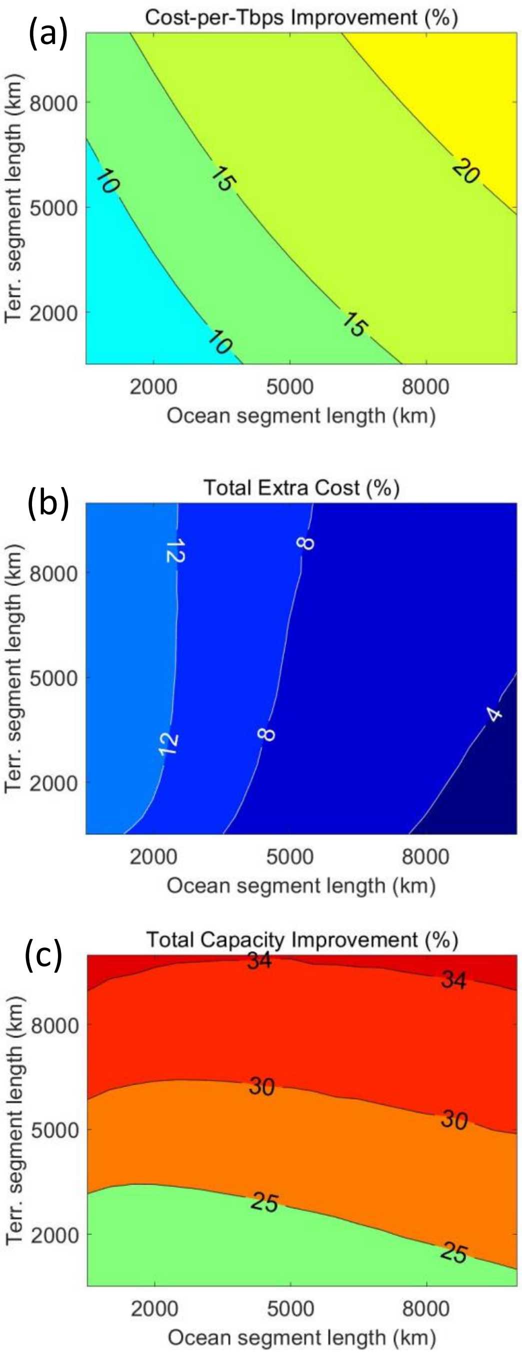

Figure 5. Comparison between a G.652 fiber solution and TeraWave SCUBA 125 one. a) 10 – 20% cost-per-bit savings (24-fiber cable with terr. EDFA NF = 6 dB) by using the TeraWave solution. b) TeraWave solution costs less than 10% more upfront and yields c) 20 – 30% more capacity.

It is found that the CPB increases 5 - 10% with higher NF amplifiers in the terrestrial segment. This effect worsens with longer terrestrial reach. However, the advanced fibers ameliorate the impact of high NF amplifiers to some degree. This model can also estimate performance for links with constrained span lengths (such as when using existing terrestrial infrastructure).

Having found the span lengths which produce the lowest CPB in the specific case of a 7,500 km mixed link, the cost savings for different combinations of ocean and terrestrial segment lengths are now computed. Figure 5 shows such a summary for TeraWave SCUBA 125 fiber using the same cable and EDFA parameters cited previously. Here the CPB is normalized to the G.652 ULL case. For each fiber type and link reach the span lengths have been optimized. This figure shows the percentage CPB savings, added total cost and added capacity of the SCUBA 125 solution relative to G.652 ULL fiber for any combination of segment lengths up to 10,000 km.

Figure 5(a) shows CPB savings of 10 – 20% with SCUBA 125 fiber over the range of link reaches. Though the cost of this solution is a few percent higher than that using G.652 fiber, (seen in Figure 5(b)), the added capacity can be as high as 30% (Figure 5(c)), thus providing an enormous benefit for the added cost. The cost savings of these fiber upgrades is enhanced for longer segment lengths. It is found that savings are even higher using SCUBA 150 fiber.

A final example illustrates the cost savings by replacement of standard terrestrial G.652.D fiber with an advanced G.654.E fiber in a mixed link. Here TeraWave SCUBA 150 is used in the ocean segment in both cases. With a 24-fiber cable and optimized span lengths in each segment, Figure 6 shows a significant CPB advantage for the G.654.E solution. The ratio between the G.654.E CPB and that of the G.652.D is

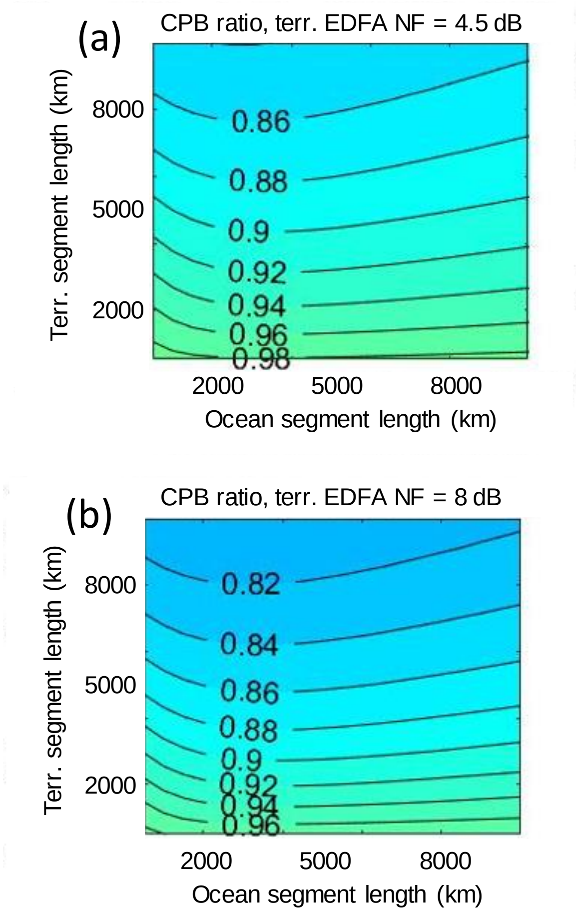

Figure 6. CPB ratio between terrestrial TeraWave ULL and G.652.D solutions (both use TeraWave SCUBA 150 in the ocean segment). TeraWave ULL provides a) 2 – 15% savings when NF = 4.5 dB, b) 4 – 20% savings when NF = 8 dB.

shown for a range of link reach. The savings increase at longer terrestrial reach and comparison of Figures 6(a) and (b) indicate the resilience of the G.654.E solution to degraded NF in the terrestrial repeaters. The savings are 5 - 8% for terrestrial segments < 2000 km. Other simulations show that with restrictions on minimum terrestrial span length (e.g. no spans < 80 km) the savings can be even higher.

6. CONCLUSIONS

Simultaneously optimizing the terrestrial and submarine components of a mixed link can result in significant cost-per-bit savings. The use of large effective area G.654.B/D/E fiber with ultra-low attenuation (such as TeraWave ULL, SCUBA 125 or SCUBA 150) in the terrestrial segment can save up to 20% compared to links using G.652.D fiber throughout. In addition, these TeraWave fibers are more robust against high NF amplifiers, which might be present in the terrestrial segment. With restrictions on minimum terrestrial span length the savings can be even higher. The relative benefits of the advanced fiber increase with longer terrestrial segments.

Results indicate that span length choices in the two segments complement one another, so that optimum link design includes longer spans in high performing (good fiber, low EDFA noise figure) segments a dependence on repeater cost. This highlights the need to do a simultaneous optimization of the terrestrial and submarine segments.

7. REFERENCES

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