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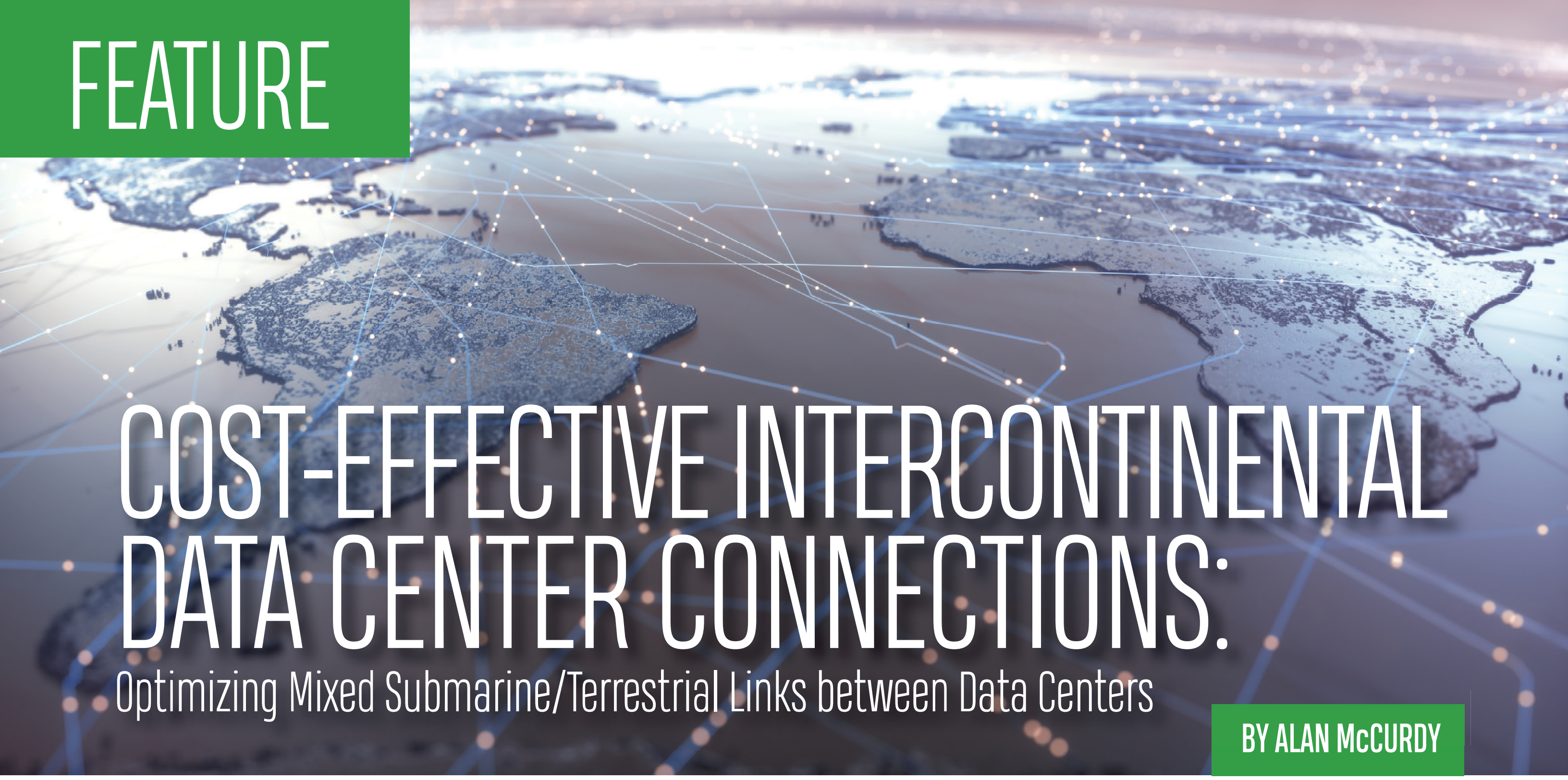

COST-EFFECTIVE INTERCONTINENTAL DATA CENTER CONNECTIONS:

Optimizing Mixed Submarine/Terrestrial Links between Data Centers

BY ALAN McCURDY

The context of any discussion about ocean cable systems has always been readily understood to mean long undersea cables that terminate in very close proximity to the beach. But business models and technology are shifting, and the "beach" is not always where it used to be. [1] A confluence of business and technology factors are driving a need for flexibility in the location of terminal equipment and an interest in blended ocean/terrestrial systems with minimal regeneration. [2, 3] And, all the while, coherent transmission technologies enable unprecedented bandwidth delivery across the same platform whether by land or sea. Systems integrators now offer products to help bridge the two network segments. [4] But how do we optimize performance when evaluating the optical path in such blended systems? And how do we chase the elusive "future-proof" objective for our physical infrastructure investment when our ocean system is not merely "ocean" anymore?

The terrestrial application space is often less static than the ocean floor, and the pathway costs are sometimes prohibitive. But there are those occasions when new terrestrial construction will necessarily accompany the establishment of an ocean system. And, in those circumstances, there are opportunities to closely mimic the performance of the ocean fiber in the terrestrial system. This may seem deceptively simple to the layman. But, in reality, it has taken advances in optical fiber design and the "open cables" approach to enable the level of seamless blending between ocean and terrestrial cables that is now possible. Being possible, however, does not automatically make it advisable.

There are many different cost contributors between ocean and terrestrial systems, and some rigorous analysis is required to discern the benefit of the seamlessly-blended approach. For illustrative purposes, we are going to compare a system employing conventional low-loss optical fiber in both the terrestrial and ocean segments to the same system employing a leading-edge fiber with a large effective area and very low loss in both segments. Substantial cost savings with leading-edge fibers and network efficiencies are obtained by optimizing combined terrestrial/ocean links. While acknowledging that long-haul systems of any sort need to be analyzed on a case-by-case basis, and might be optimized with a combination of fibers, the intent is to show the process of evaluating a solution and the possibilities that are now available.

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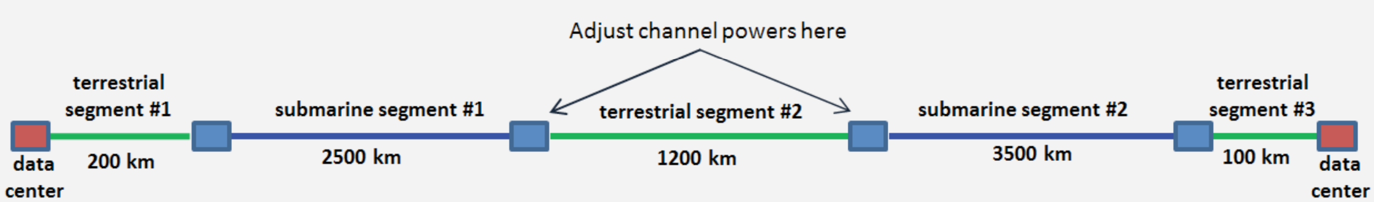
The two properties of modern fibers which are most important in this regard are attenuation and optical mode field diameter (or equivalently, mode effective area). Low attenuation preserves the signal through the link with lower required amplification. Amplifiers generate noise so the less gain required 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 that submarine fibers use today is 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" or CPB. This is a ratio of the total costs: deployment, cable, optical fiber, repeaters, and more 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 is made to verify that this new component will provide enough added capacity to justify its additional cost. Our studies indicate 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 or D) as opposed to conventionally-sized ULL optical fibers. An example will be shown here using OFS TeraWaveâ SCUBA fibers throughout a mixed terrestrial/submarine link.

MEASURING LINK PERFORMANCE

Figure 1 shows a sample link of 7,500 km, connecting two data centers, which includes both terrestrial and submarine segments. In practice, there can be any number of segments of each type interspersed in an arbitrary way. We can cost out various solutions using combinations of the various fiber types shown in the chart. In making the fiber choices, we could consider using cheaper terrestrial amplifiers (such as erbium doped fiber amplifiers with higher noise figure (NF)) or varying the distance between repeaters in either the submarine or terrestrial segments to save on cost. Submarine costs are estimated for the items mentioned previously, with a similar approach taken to the terrestrial portion of the network. Additional features to terrestrial costing 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).

Given that we have a cost model for each component in our proposed link, we now need to estimate the link performance. The electrical signal-to-noise-ratio (SNR) is a favored metric of system designers today. It is a ratio 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. If we assume transmission gear capable of operating within "X" dB of the Shannon limit (a fundamental limit on the capacity of a noisy information channel), then we can compute the link capacity without knowing details of the end terminal equipment. This is advantageous today because terminal equipment can often be reconfigured through software to transmit any one of a large group of transmission formats



ITU Fiber Type (with OFS product)	Historical Usage	Attenuation	Effective Area
G.652 (AllWave® LL)	terrestrial	low (0.184 dB/km)	standard (83 μm^2)
G.652 ULL	terrestrial/ submarine	lower (0.170 dB/km)	standard (82 μm^2)
G.654.B/D (TeraWave® SCUBA 125)	submarine	ultra-low (0.155 dB/km)	large (125 μm^2)
G.654.D (TeraWave® SCUBA 150)	submarine	ultra-low (0.154 dB/km)	ultra-large (153 μm^2)

Figure 1. An example 7,500 km link connecting two data centers using both submarine and terrestrial segments. Also shown are a number of optical fiber types and their typical properties (OFS products shown in parentheses).

(QPSK, 8-QAM, 16-QAM, etc.) depending on the capabilities of the link infrastructure. Also, terminal equipment capabilities may improve during the time between cable deployment and lighting up the fibers. The value for "X" today is roughly 6 – 7 dB, which includes enough margin to allow some degradation of the infrastructure over time, without causing a network outage. So by calculating SNR for each proposed link, we can use the Shannon formula to estimate the likely capacity of our choice. The cost/capacity ratio then allows us to find the CPB.

OPTIMUM MIXED LINK DESIGN

While long distance optical link simulations used to take a lot of CPU time on a workstation, a common tool today is the widely accepted Gaussian Noise Interference Model (GNI), which requires little more than a spreadsheet. 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 SNR can be estimated quite accurately, even in the nonlinear regime (where optical channel powers are high). Fortunately, optimum link optical performance is obtained when the properties of each span length (repeater spacing) are individually optimized. This means that the optimum optical channel power can be found for each span, independent of all the others. With some spans on land and some in the ocean, we may find the best performance using different fiber types in each, operating at different channel power. It turns out that the order of these spans is not important. So, all the terrestrial segments of the overall link can be combined into one long segment, and all the submarine segments can be combined into another long segment. Thus we have a link with two parts: one terrestrial and one submarine. We assume here that none of the submarine segments is long enough to encounter electrical power feed equipment limitations (though this can be incorporated into the model). We then apply the appropriate technology to each segment: fiber type, repeater characteristic (NF), span length, and costs.

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 in the ocean segment because of the extra losses (splices), higher EDFA NF, and cheaper amplifiers of the terrestrial segment. Figure 2 shows the CPB (normalized dollars per terabit-per-second) in level contours for the 7,500 km link (described in Figure 1) using three different fiber choices. Here we have used the same fiber throughout the link to emphasize the added performance of the large effective area submarine fibers (SCUBA 125 fiber and SCUBA 150 fiber) in the terrestrial segment.

The circular contours 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 also demonstrates that terrestrial span lengths can be increased with the SCUBA fiber. The result is nearly a 20% cost savings when using SCUBA 150 fiber throughout the link rather than G.652 ULL fiber. 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, we can now ask more generally what cost savings can be obtained with different combinations of ocean and terrestrial segment lengths. Figure 3 shows such a summary for TeraWave

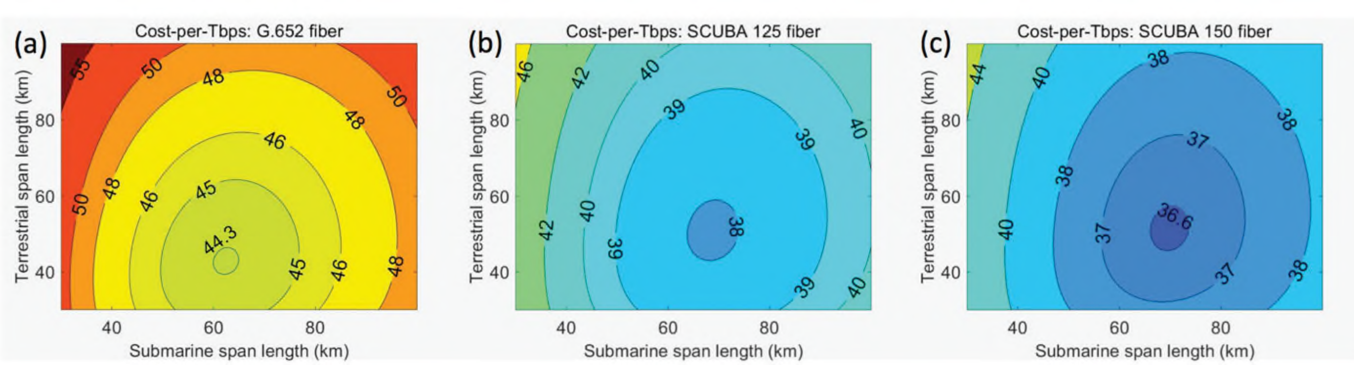


Figure 2. Normalized cost per Tbps in a 7,500 km link (6,000 km ocean and 1,500 km terrestrial) using different fibers: (a) G.652 ULL (ocean) with G.652 fiber (terrestrial), (b) TeraWave SCUBA 125 fiber throughout and (c) TeraWave SCUBA 150 fiber throughout. EDFA NF = 6 dB (terrestrial), 4.5 dB (ocean) and a 24 fiber cable assumed. Red indicates high cost and blue shows low cost.

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 fiber solution relative to G.652 ULL fiber for any combination of segment lengths up to 10,000 km.

Figure 3(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 3(b)), the added capacity can be as high as 30% (Figure 3(c)), thus providing an enormous benefit for the added cost. The cost savings of these fiber upgrades is enhanced for longer segment lengths. And savings are even higher using SCUBA 150 fiber.

In addition, 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. Also, optimum terrestrial span lengths decrease with increasing EDFA NF. This is because the SNR is more difficult to maintain with high NF, and a cost trade-off is made. Finally, the optimum submarine span length increases when a terrestrial performance decreases (due to either high NF or poor performing terrestrial fiber). This indicates that the cost (closely spaced repeaters) of obtaining high capacity in the submarine segment is not justified when the terrestrial segment is impaired.

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 fiber with ultra-low attenuation (such as TeraWave SCUBA 125 or SCUBA 150 fibers) 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 (e.g. no spans < 80 km), the savings can be even higher. The relative benefits of the advanced fiber increase with longer terrestrial segments and higher terrestrial EDFA noise figure.

The 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. This highlights the need to do a simultaneous optimization of the terrestrial and submarine segments. STF

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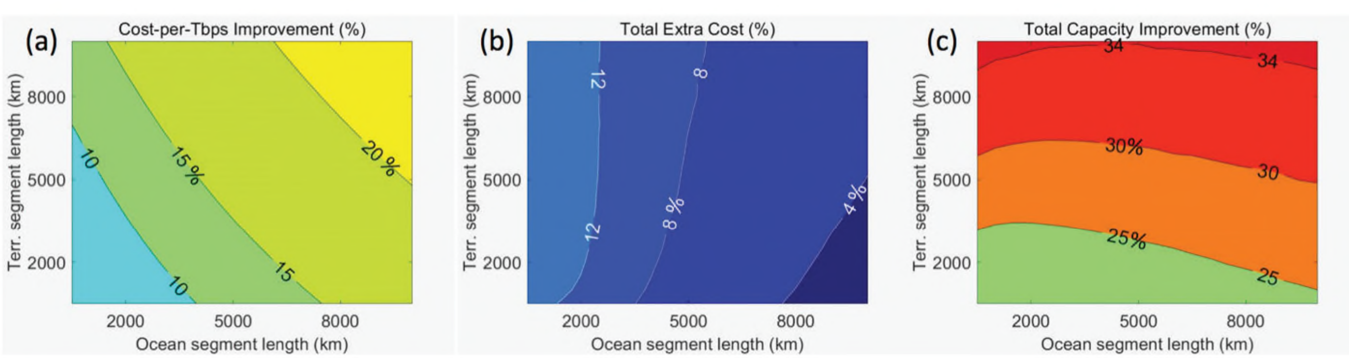

Figure 3. Comparison between a G.652 fiber solution and TeraWave SCUBA 125 fiber. (a) 10 – 20% cost-per-bit savings (24-fiber cable with EDFA NF = 6 dB) by using the TeraWave fiber solution. (b) TeraWave fiber solution costs less than 10% more upfront and yields (c) 20 – 30% more capacity.