FEATURE

UNDERSTANDING THE IMPORTANCE OF TERRESTRIAL BACKHAUL NETWORKS TO END-TO-END SUBMARINE NETWORK SERVICES

BY BRIAN LAVALLÉE, RICHARD NORRIS, DARWIN EVANS, SERGEJS MAKOVEJS, LIDIA GALDINO, AND PASCAL PECCI

There's a critical symbiotic relationship between submarine and terrestrial networks and operators, which is the foundation of the global internet and associated socioeconomic benefits enjoyed by all connected citizens of Earth. Submarine cable networks are critical infrastructure in an increasingly connected world, but they are only part of the end-to-end connection story, as traditional Communications Service Provider (CSP) central offices and Internet Content Provider (ICP) data centers can be located tens to hundreds of kilometers inland. This means that the terrestrial network segments on each end of any submarine cable are critical parts of the end-to-end story for Data Center Interconnection (DCI) applications, and even non-DCI services terminating in traditional telecom central offices.

TRADITIONAL SUBMARINE NETWORK AND TERRESTRIAL NETWORK DEMARCATION

Traditional submarine cables traversed ocean floors and were terminated in Cable Landing Stations (CLSs) on or very close to the coastlines. They were then connected to terrestrial backhaul networks on both ends of the subma-

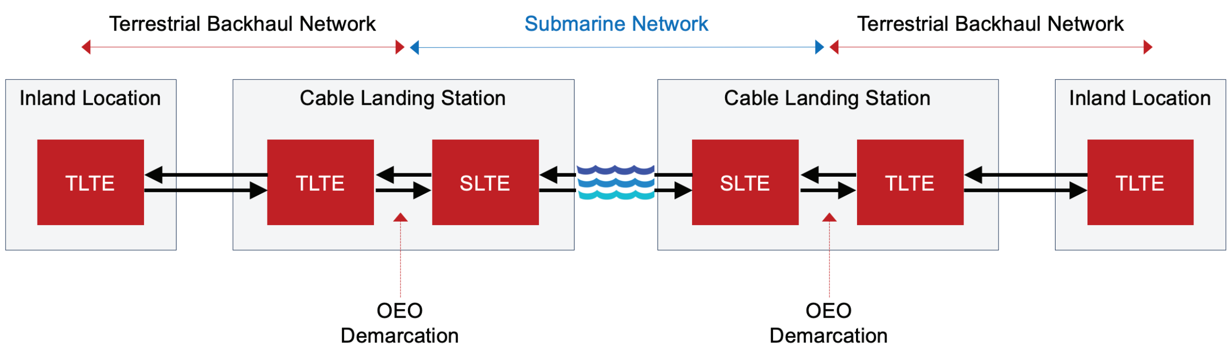

Figure 1: Distinct, yet interconnected, submarine networks and terrestrial networks.

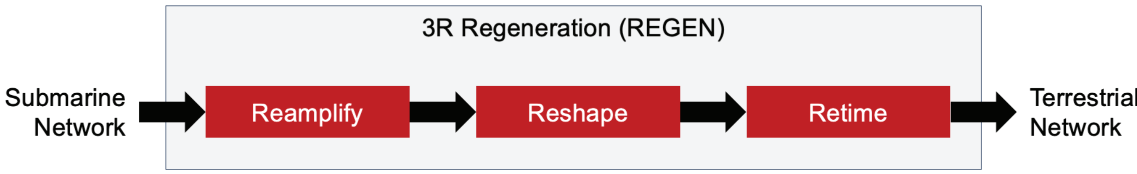

Figure 2: Traditional 3R (Reamplify, Reshape, Retime) regeneration stage.

rine cables that terminated services initially in central offices but increasingly in data centers, as shown in Figure 1. It was common for submarine cables to be owned by multiple owners in a consortium, connected to two different terrestrial network operators. Because of a clear demarcation between these three networks, the cables were often designed in isolation from one another, with only the total amount of landed submarine cable capacity considered by terrestrial backhaul network operators. The optical transmission modem technology in Submarine Line Terminal Equipment (SLTE) and Terrestrial Line Terminal Equipment (TLTE) could be, and often was, different.

Between the SLTE and TLTE, 3R (Reamplify, Reshape, Retime) regeneration was performed by REGENs via an Optical-Electrical-Optical (OEO) stage. In other words, the signals received from the submarine cable were "cleaned up" and matched to the terrestrial backhaul network line system of optical Erbium-Doped Fiber Amplifiers (EDFAs) and optical fiber type. Although submarine and terrestrial backhaul networks were interconnected, they were distinct networks owned and managed by different operators that often chose their fiber types in isolation with just capacity having to match.

OPTICAL BYPASS

The advent of coherent optical transmission, initially adopted by TLTE but rapidly adapted to SLTE, changed how submarine networks—and the terrestrial backhaul networks at each end—were designed. When coherent optical transmission technology was used in conjunction with Reconfigurable Optical Add/Drop Multiplexers (ROADMs), the Optical Bypass architecture was rapidly implemented. The combination of these two technologies allowed for simpler end-to-end network designs, overland and undersea, that not only removed a lot of equipment, but also resulted in network designs that did away with multiple CLS OEO stages—meaning less equipment, power, space, and lower overall latency, as shown in Figure 3. These simpler network designs enabled higher capacities at a much lower per bit cost.

As shown in Figure 3, the SLTE is moved inland and a ROADM is placed in the CLS to perform traffic switching of wavelengths and spectrum, as well as wet plant power management. And, as the telecom industry moves towards greater openness, the Open Cable business model has been adopted by the submarine networking market. This provides submarine cable operators with a broader vendor ecosystem to accelerate innovation via greater choice to design best-in-breed submarine networks.

Although there are several benefits to the much simpler Optical Bypass architecture, it does raise some challenges that must be addressed. Given the SLTE is moved inland on the other side of the terrestrial backhaul network and the OEO regeneration stages are eliminated, the end-to-end network performance must now consider the terrestrial backhaul network and submarine network line systems comprised of optical amplifiers, ROADMs, and the fiber itself. The latter is the focus of this article, where the performance and selection of terrestrial backhaul network fiber cannot be

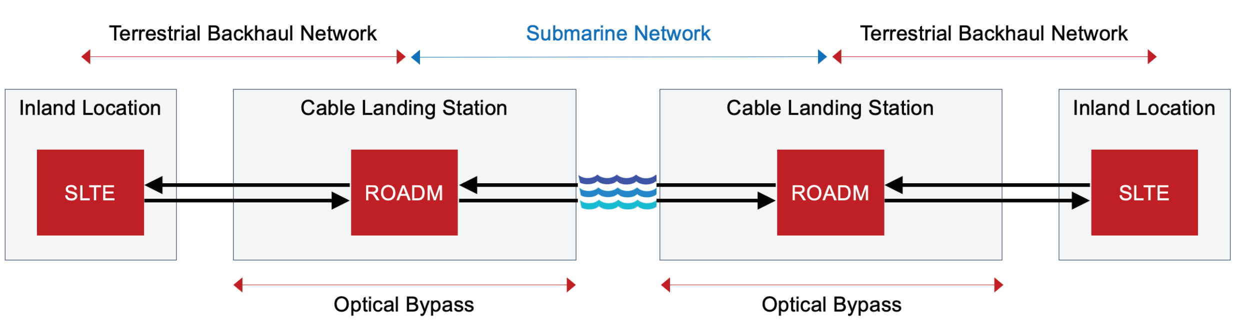

Figure 3: Simpler end-to-end network design via coherent optical transmission (GeoMesh Extreme).

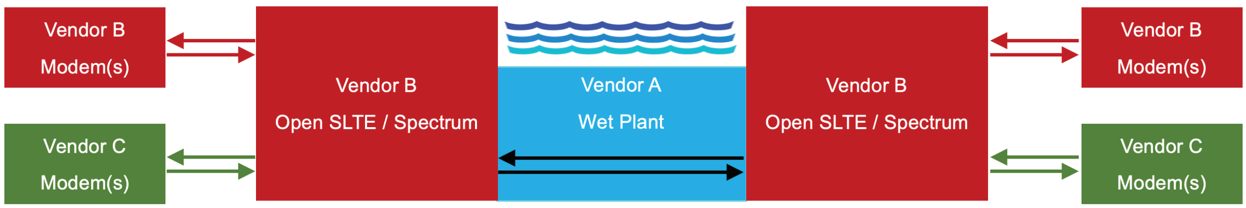

Figure 4: Open cable business model providing greater choice.

made in isolation from the wet plant, as the SLTE coherent optical transmission occurs over all three segments.

ADVANCED TERRESTRIAL OPTICAL FIBERS

The two key optical fiber characteristics that affect transmission performance are attenuation and Aeff (effective area). The benefit of ultra-low attenuation is well understood and seen as a good measure for glass purity with the outcome being the lower total amount of noise accumulated from the chain of optical amplifiers. On the other hand, the use of large Aeff fibers has historically been less common in terrestrial networks. It was not until late 2016 when the ITU-T ratified the use of large Aeff fibers, paving the way toward a significant growth of such fiber deployment over the past several years. The simplest way to visualize the impact of fiber Aeff, is to consider that in those fibers the light is spread over a wider fiber cross-section area compared to a regular fiber, as shown in Figure 5. This mitigates the impact of nonlinear impairments while allowing for a higher optical launch power into the fiber to increase the Signal-to-Noise Ratio (SNR). To maximize overall transmission performance, fiber attenuation must be decreased, and its effective area increased while maintaining acceptable bend performance and single-mode transmission behavior. Optical fiber types with these characteristics are referred to as “advanced.”

The importance of such advanced fibers is especially pronounced in Optical Bypass network designs, as shown in Figure 3. As the length of the terrestrial backhaul network increases, the submarine cable capacity is reduced. This an undesirable effect since every Terabit per Second (Tb/s) worth of submarine cable capacity has a monetary value associated with it. So, losing capacity means leaving money on the table for a reduced overall Return on Investment (ROI). The choice of terrestrial backhaul network fiber cannot undo the effect of submarine cable capacity reduction, but it can significantly mitigate it. In other words, the use of advanced terrestrial fibers can preserve some of the high-value submarine cable network capacity when compared to regular G.652.D fibers and even more so, legacy G.655 fibers.

In areas where deploying new cable routes represents a viable option, advanced terrestrial fibers should always be considered. Modern cable designs can contain mixed fiber types, allowing for a scenario where a certain portion of the cable consists of an advanced fiber to provide transit of submarine cable traffic terrestrially, while the remainder of the cable consists of a regular G.652.D fiber to serve more

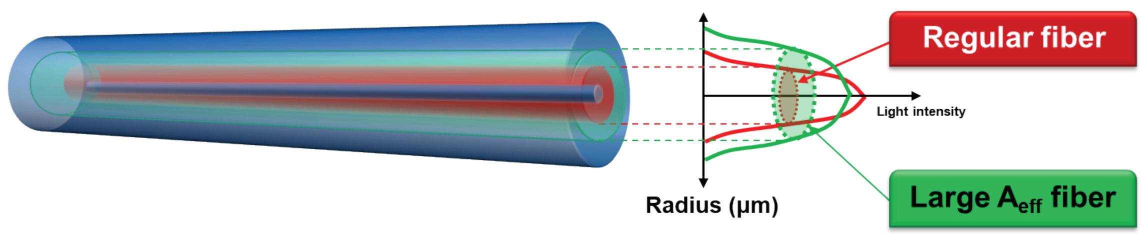

Figure 5: Visualizing the benefit associated with large fiber Aeff.

Table 1: Submarine cable key parameters used in the study.

Parameter	Value
Cable length	7,000km
Number of repeaters	100
Average span length	70km
Fibre type	Corning® Vascade® EX2500
Fibre loss/km	0.149 dB/km
Fibre Aeff	125 um2
Chromatic dispersion	20.8 ps/nm/km
Repeater TOP	16.5 dBm
Repeater gain	10.6 dB
Repeater noise figure	4.5 dB
Repeater spectrum	4.5 THz
Manufacturing margin	1 dB

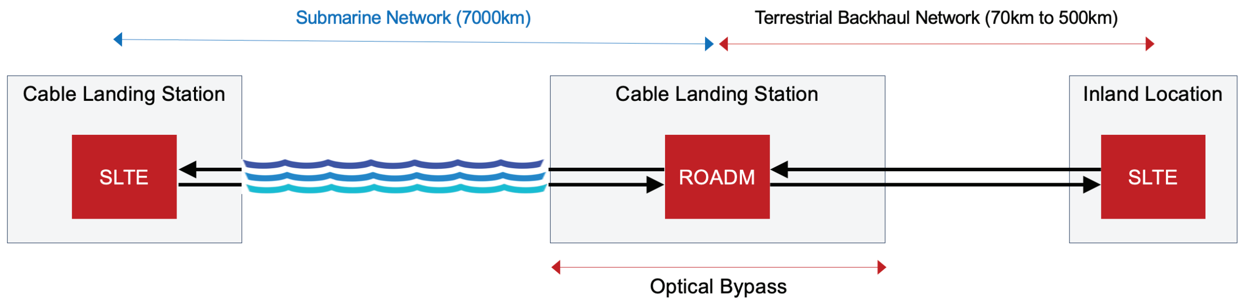

Figure 6: Modelling study network diagram used.

conventional bandwidth needs. Assuming the latest transatlantic Spatial Division Multiplexing (SDM) cable design containing 24 Fiber Pairs (FPs), one would need at least 48 advanced fibers in the terrestrial backhaul network to directly map each submarine fiber to each terrestrial fiber.

It's recommended the overall number of fibers per submarine cable accurately reflects future needs as well. As we get ever closer to the Shannon Capacity Limit, spectral efficiency (overall capacity) per fiber is quickly saturating—meaning new SLTE technology cannot provide massive step increases in submarine cable capacity to address ever-growing global bandwidth growth. Future SLTE upgrades will still provide increases, albeit smaller improvements in spectral efficiency gains and total capacities achieved with far fewer modems, resulting in greener network designs. High-fiber-count SDM cables allow us to "sidestep" the Shannon Capacity Limit by leveraging more FPs for higher overall submarine cable capacities, even though the per FP capacity is lower than traditional non-SDM wet plants. The vast increase in SDM wet plant capacities makes terrestrial network fiber selection even more critical for optimized end-to-end network performance.

Table 2: Submarine cable performance.

Item	Result
Cable GSNR	12.3 dB
Fiber Pair (FP) capacity	24.7 Tb/s
Cable capacity	593 Tb/s

OPTICAL FIBER STUDY AND RESULTS

To investigate the impact of different terrestrial optical fiber types on overall end-to-end performance and capacity, we conducted a study using a reference submarine cable combined with a range of terrestrial backhaul networks. The performance of each end-to-end route, overland and undersea, was recorded and then the capacity was determined using the latest generation of Ciena's WaveLogic 6 Extreme modems and 6500 Reconfigurable Line System (RLS). The design of the submarine cable was fixed throughout allowing the impact of just the terrestrial backhaul network to be clearly understood. The end-to-end network used in the modelling study is shown in Figure 6. The key parameters used for the submarine cable are shown in Table 1.

Using the key parameters shown in Table 1, we simulated the performance of just the submarine cable to determine the Generalized Signal-to-Noise Ratio (GSNR) and the associated capacity. The capacity value includes industry standard margins and is for a 24 FP SDM cable. The simulation work produced the results shown in Table 2.

With the submarine cable performance and capacity used as a baseline, we then investigated the impact of ex-

Table 3: Terrestrial backhaul network route ranges.

Fibre Type	Span Length (km)	Number of Spans	Total Length (km)
Vascade EX2500	70	1 to 7	70 to 490
Vascade EX2500	100	1 to 5	100 to 500
SMF-28 Ultra	70	1 to 7	70 to 490
SMF-28 Ultra	100	1 to 5	100 to 500
NZDSF (G.655)	70	1 to 7	70 to 490
NZDSF (G.655)	100	1 to 5	100 to 500

Table 4: Terrestrial fiber key parameters used in the study.			
Item	Vascade EX2500	SMF-28 Ultra	NZDSF
Effective area (µm2)	125	80	72
Loss/km (dB/km)	0.149	0.181	0.25
Chromatic dispersion @ 1550nm (ps/nm/km)	20.8	17	4.5
Polarization mode dispersion (ps/√km)	0.1	0.1	0.1
Nonlinear index (n2) (m^2/W)	2.1x10-20	2.3x10-20	2.3x10-20
Non-linear coefficient (W^-1 km^-1)	0.68	1.16	1.3
Peak Raman gain coefficient (km^1*W^-1)	0.2	0.41	0.45
Splice loss to self (dB)	0.03	0.03	0.03
Splice loss to 80 µm2 pigtails (dB)	0.1	0.03	0.05
Length between splices (km)	6	6	6
Head/tail patch loss (dB)	0.5	0.5	0.5
Span margin (dB)	1	1	1

tending services over a range of terrestrial backhaul network routes. The range of such routes included three different fiber types, two different span lengths, and total lengths up to 500km. The terrestrial backhaul network equipment used in the study is the latest generation of Ciena products with only EDFAs used; no RAMAN amplification was used in the network designs. The range of terrestrial backhaul network routes is shown in Table 3.

The three fiber types used represent a range with Vascade EX2500 fiber providing the best transmission performance and aligned to that used in the submarine cable. SMF-28 Ultra fiber is a medium option with reduced performance compared to Vascade EX2500 fiber. Finally, a non-zero dispersion shifted fiber (NZDSF) has a lower performance than the other two fiber types. The key parameters for the three fiber types are shown in Table 4.

The final stage of the study was to combine the submarine cable with each terrestrial backhaul option and look at the total end-to-end performance and associated capacity. This was done based on the latest generation of Ciena equipment with transponders at the end points only (no intermediate regeneration). The GSNR versus terrestrial distance versus fiber type results are shown in Figure 7 below. The standard Ciena solution uses a Dynamic Gain Equalizer (DGE) after 4 terrestrial spans, which can be seen as a slight performance improvement in each plot.

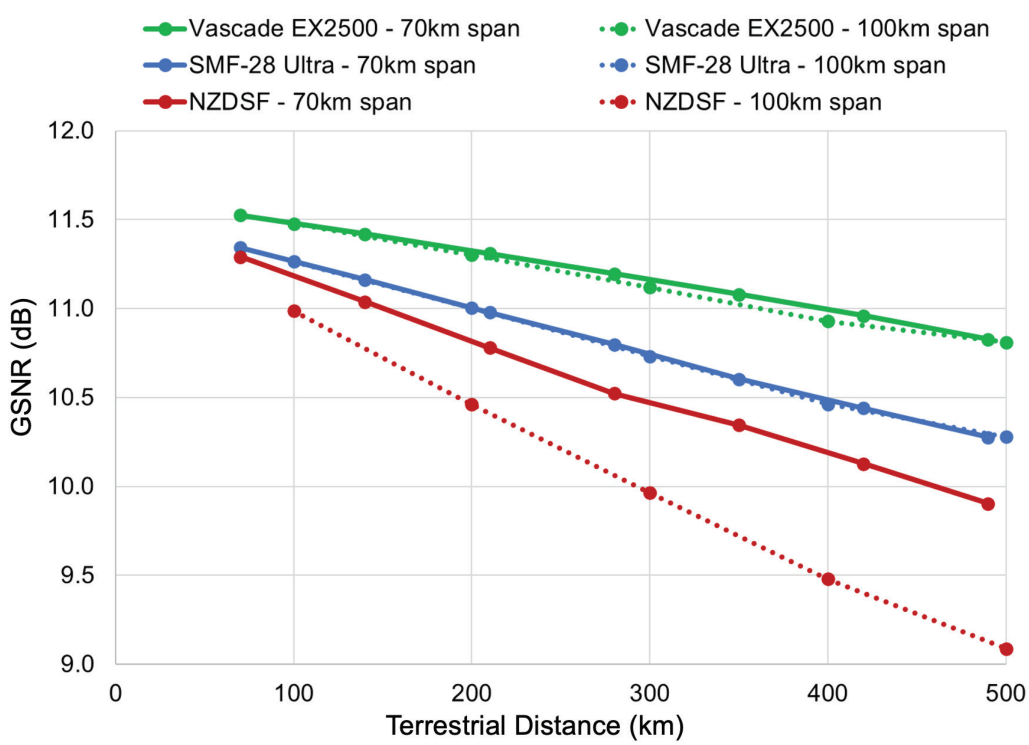

Figure 7: End-to-end system performance.

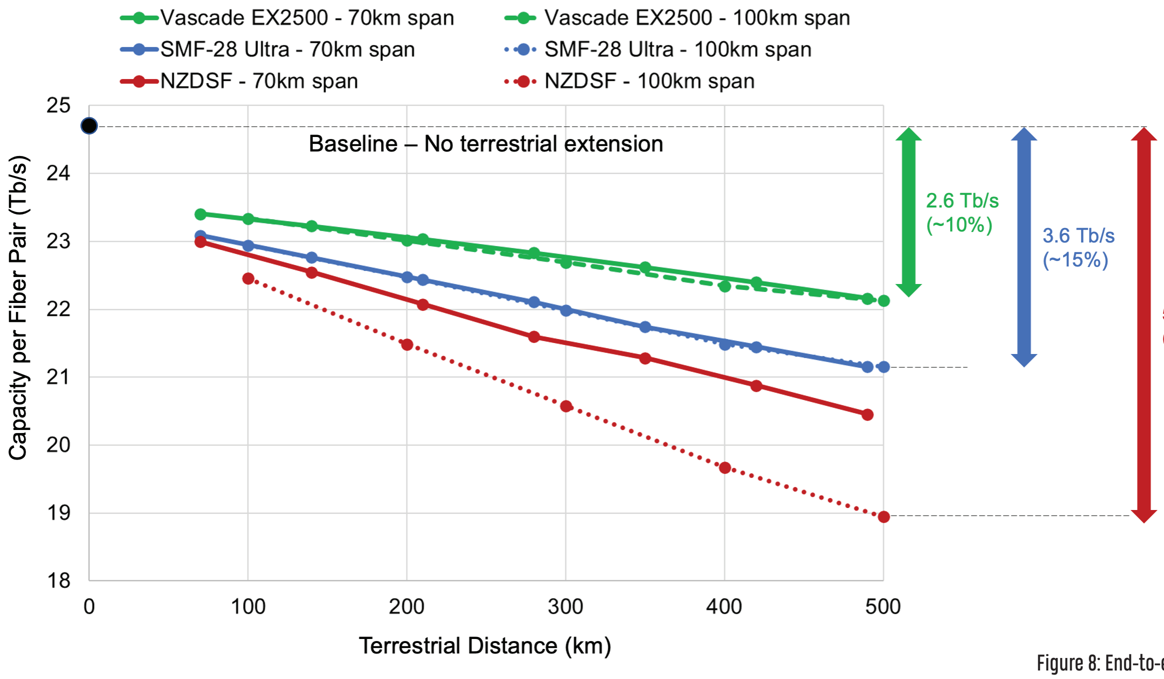

Figure 8: End-to-end system capacity.

The end-to-end submarine cable plus terrestrial backhaul system performance can then be translated into per FP capacity to see the impact of the different terrestrial fiber types. Figure 8 illustrates the end-to-end per FP capacity versus terrestrial backhaul network distance versus fiber type.

INTERPRETING THE STUDY FINDINGS

It can clearly be seen that the terrestrial network backhaul design has a significant impact on total end-to-end system performance and associated capacity. The performance reduction with terrestrial backhaul network length is relatively linear. Network designs based on Vascade EX2500 fiber in the terrestrial section have the lowest end-to-end performance reduction of all fibers studied in this work.

The span lengths of the terrestrial backhaul networks also impact end-to-end system performance, although by a different amount per fiber type. Designs based on Vascade EX2500 fiber have a small performance difference between the design with 70km spans versus the design with 100km spans. This is expected, as fiber loss is very low, so terrestrial network EDFAs are operating with good margins. Designs based on SMF-28 Ultra fiber exhibit a similarly small span-dependent performance variation since the fiber loss is still relatively low, although the absolute performance is lower compared to Vascade EX2500 fiber, as noted earlier. However, NZDSF-based designs show a large performance difference between 70km and 100km span designs. This is because of fiber loss being high at 0.25dB/km and span loss at 100km being at the upper edge of the EDFA performance range.

BUSINESS BENEFITS OF THE STUDY RESULTS TO CABLE BUYERS

Every terrestrial backhaul network should be designed with specific submarine cable network capacity requirements from an end-to-end perspective. While we should always work to design high-quality terrestrial backhaul network spans for optical performance and network availability purposes, terrestrial extensions of submarine cables require special consideration for optimal optical performance. Submarine cables are very expensive, and FPs are limited in quantity with a very long lead-time to build more, so unnecessarily losing submarine cable capacity must be avoided.

Over the past decade, submarine cable designs have evolved from high Total Output Power (TOP) for repeaters (20dBm and higher), high Aeff (150um2) fiber, and high capacity per FP (25Tb/s and higher) to an SDM design, which is more energy efficient and allows for 300Tb/s to 500Tb/s total cable transatlantic capacities while leveraging existing Power Feed Equipment (PFE). SDM cables leverage repeater (undersea EDFA) pump-sharing technology where optical pump power is shared between multiple (typically four) FPs and provides up to 24 FPs—with higher fiber counts already being discussed. Over transatlantic distances, the per-FP capacity has been decreased by 20% (typically 20Tb/s now versus 25Tb/s previously) and the submarine cable SNR reduced by multiple dBs.

With new terrestrial fiber types, the penalty associated with concatenating submarine and terrestrial backhaul networks can be reduced one step further. Consequently, for a submarine cable buyer, we must decide where regeneration should be done, knowing the target is to limit the lost submarine cable capacity and ensure the power and space required for SLTE regeneration is at the right physical location, as it's not always possible to have the required space and power available in a CLS.

If we consider submarine cable systems are $30K to $50K per km, a 7,000km transatlantic submarine cable can cost upwards of $350M. Increasing the terrestrial network length from 0km to 500km results in a capacity loss of ~15% and a monetary loss of ~$52.5M, when using SMF-28 Ultra fiber. Using NZDSF results in a higher capacity loss of ~23% and monetary loss of ~$80M. Using a more advanced fiber, like Vascade EX2500, capacity loss is reduced by ~10% with a lower monetary loss of ~$35M. In other words, Vascade EX2500 fiber, compared to SMF-28 Ultra, provides an additional monetary value of $17.5M, which is significant in terms of reducing the total cost of ownership.

This work excludes additional costs associated with securing rights of way and new cable deployment on the terrestrial side, which can be very high and can prevent the deployment of the new cable, particularly if there is a cable that is already in the ground. That said, deploying a new cable may be a matter of necessity, if the optical quality of the old cable has decreased below the acceptable level, or if there is no existing cable in the first place. In some cases, however, the terrestrial carriers may have multiple ducts (or miniducts) that are already present in the ground, and those ducts may be empty. If so, the new cable can simply be pulled or jetted through the existing ducts, thus significantly reducing the new cable installation costs. To further accelerate Ready for Service (RFS) dates, submarine cable and terrestrial backhaul network permits should be managed in parallel to avoid additional delays.

NO 'ONE SIZE FITS ALL'

In conclusion, there's no one-size-fits-all network design answer for terrestrial backhaul networks attached to the ends of typical submarine cables, although one should always aspire to choose the best performance fiber in the terrestrial section, if possible. Configurations (regeneration in the CLS as opposed to a location several to hundreds of kilometers inland) must be carefully studied in advance, taking into account the availability of required power and space, the impact of the terrestrial backhaul networks on overall end-to-end total capacity, the possibility to lease terrestrial backhaul network fiber, and in particular, the terrestrial backhaul span distances and associated losses, as well as fiber quality. As illustrated in the study, new terrestrial fiber types provide operators with greater choice and performance. STF

BRIAN LAVALLÉE *is Senior Director of Solutions Marketing with global responsibility for various segments including 5G, Submarine, Edge Cloud, Satellite, and others. An industry veteran, he has more than 20 years of telecommunications experience with previous roles in Product Line Management, Systems & Network Engineering, Research & Development, Business Development, and Operations. In his career, he's worked in numerous areas related to packet and optical networks from access to submarine networks, and everything in between. Brian holds a Bachelor of Electrical Engineering from Concordia University and an MBA in Marketing & International Business from McGill University, both located in Montréal, Québec, Canada.*

DARWIN EVANS *is the Director of Product Line Management for submarine applications at Ciena. In this role, he is responsible for creating the roadmap for Ciena's modem and photonic submarine solutions. Prior to joining Ciena, Darwin worked in several engineering and product development roles at Nortel Networks until the acquisition of the Nortel Metro Ethernet Networks division by Ciena in 2010. He has served in his current role at the company since 2015. Darwin received his B.S. in computer engineering from the University of Manitoba.*

RICHARD NORRIS *is Senior Director of Global Submarine System Engineering at Ciena, with responsibility for submarine solution technical sales and development. Well established in the telecom industry for 25 years, Richard works for both vendors and operators, and first became involved in submarine networking in the 1990s, where he was the technical representative on a number of new cable consortia projects. Since then, Richard has held various leadership positions at Ciena, where he continues to be heavily involved with the submarine networking industry He holds a bachelor's degree in Electronic Engineering from the University of Central Lancashire and resides in the UK.*

PASCAL PECCI *is Submarine Cable Systems Engineer at Meta. He worked during 25 years for Alcatel (Lucent, Submarine) in terrestrial (15 years) and submarine (10 years) networks as researcher, designer, Product Line Manager, Marketing Responsible and Technical Project Manager. He is a Distinguished Member of the Technical Staff. Since 2023 he joined Meta as a Senior Submarine Cable Systems Engineer and is leading multiple submarine projects.*

SERGEJS MAKOVEJS, *Sr. is Commercial Technology Associate at Corning. Sergejs Makovejs has global responsibility for market development and product strategy for long-haul and subsea fibers at Corning. He received a Ph.D. in Electrical Engineering from UCL, UK in 2011 and an Executive MBA from Warwick Business School, UK in 2019. Sergejs has authored >60 papers in the field of optical fiber communications. He is a regular presenter and a frequent member of technical subcommittees at major industry events.*

LIDIA GALDINO *is a System Engineering Manager at Corning, responsible for defining and driving long-haul terrestrial and submarine optical fiber and cable product strategy. She received a Ph.D. from University of Campinas. She is an Associate Editor for the Journal of Lightwave Technology, and serves on several technical program committees, including OFC and ECOC. She has authored > 100 peer-reviewed papers on optical fiber communication systems.*