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Benefits of TeraWave™ ULL Optical Fiber for Improving Capacity, Reach, and Economics with Coherent Transport

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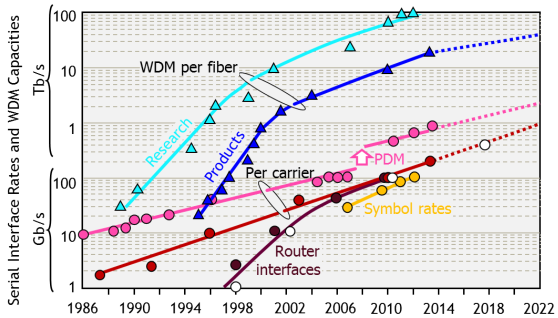
Summary

Today coherent transport technology enables 40 and 100 Gigabit per second speeds over legacy fiber networks, but soon new developments will enable even higher data rates up to 400 Gb/s and beyond over a new generation of low loss, large area fibers. In response to the advances in signaling technologies, OFS introduced the TeraWave ULL Optical Fibers designed for emerging terabit per second modulation formats. The deployment of cable including TeraWave ULL Optical Fiber will help network operators better manage emerging, fundamental limitations in spectral efficiency and un-regenerated reach to help reduce cost-per-bit of transport as traffic grows exponentially. TeraWave ULL Optical Fiber transports coherent modulation formats almost twice as far as the installed base of G.652 standard single-mode fiber (SSMF) without regeneration. It has been optimized for use in both the C- and L-bands. The cost-per-bit from procuring and fully lighting a cabled TeraWave ULL Optical Fiber can be 40 to 80% lower cost-per-bit than fully lighting a legacy G.652 fiber over an erbium-doped fiber amplifier (EDFA) chain, typical of the installed base, by avoiding the high cost of regeneration.

Fundamental Technical Challenges for the Internet

In order to maintain the same revenue, traditional network operators must carry about ~30% more traffic each year, while cloud providers must transport up to ~50% more data each year. This implies that the marginal cost per bit for backbone transport must also continue to decrease, in order to maintain network economics. Two key technology factors have helped make this possible since 1991. One is the ability to increase capacity of transport at an average rate of ~50% year over year, and the other is the ability to maintain the un-regenerated reach of optically amplified links as capacity increased. This increase in capacity has resulted from the ability to go from one to 100 wavelengths in the C-band of EDFA by dense wave-division multiplexing (DWDM) as well as the increase in spectral efficiency (S.E.) by moving from 2.5 Gb/s to 100 Gb/s within the 50 GHz ITU grid. Together these two trends allowed operators to avoid lighting up new fibers too quickly as traffic grew, thereby minimizing the high cost of regeneration. Fig. 1 shows the historical growth of capacity for commercial DWDM products, taken from Ref [1], focusing on the dark blue line labeled “Products.”



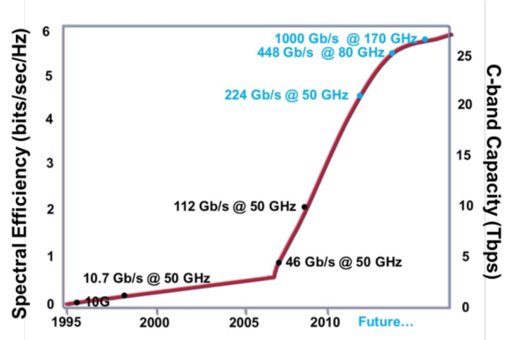


Fig. 1: Growth of system capacity due to increasing speeds of single wavelength, wavelength and polarization multiplexing, and use of advanced modulation formats. Dark blue triangles are commercial DWDM systems. Growth of total capacity has slowed since 2002 and is predicted to slow further. From Ref. [1]

Fig. 2: Growth of spectral efficiency, in the past and extrapolated. Spectral efficiency growth is predicted to slow beyond 200 Gb/s, after which the signal no longer fits into a 50 GHz ITU channel. From Ref [2].

The key to growing capacity is being able to increase S.E. This term refers to the density of data being transported within the spectral bandwidth of the optical amplifier, in bits/second/Hz, which can be calculated by dividing the data rate in Gb/s by the width of the channel in GHz. Since the advent of the erbium-doped fiber amplifier (EDFA) and dense wave division multiplexing in the mid-90's it has been possible to greatly increase S.E. because signals from higher speed transponders normally fit inside the 50 GHz ITU channels. For example, the move from 10 Gb/s to 100 Gb/s represents an increase in S.E. from 0.2 b/s/Hz to 2 b/s/Hz. The C-band EDFA typically supports 80 to 100 channels in 35 to 40nm of spectrum, rendering the capacity of a fiber fully lit in the C-band of approximately 10 Tb/s.

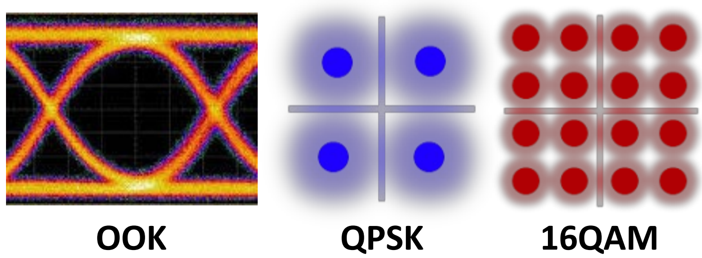


Fig. 3: The on-off keying (OOK) eye diagram (left) supports one bit per symbol using direct detection. The quadrature phase-shift keyed (QPSK) constellation (center) supports two bits per symbol, while the higher order quadrature amplitude modulation (16QAM) constellation (right) supports four bit per symbol, requiring a coherent receiver. For the same Baud rate, the 16QAM format supports twice the S.E. of QPSK, which supports twice the S.E. of OOK. In fact, the two coherent constellations show are used – in conjunction with polarization multiplexing and 32 GBaud signaling – to support 100 Gb/s and 200 Gb/s transmission in modern coherent systems, respectively.

It is widely considered that the move from 100 Gb/s (Pol-mux QPSK) to 200 Gb/s (Pol-mux 16QAM) is the last long haul line rate increase for which doubling speed will double capacity for a long-haul system. See for example Fig. 2. This is because future increases will require either increasing the Baud rate beyond ~32 GBaud or else using two wavelengths. Regardless, the 400 Gb/s channel will be wider than 50 GHz. Practically, the next 10 fold increase in bit rate from 100 Gb/s to 1 Tb/s may be accompanied by at most a four-fold increase in spectral efficiency, and therefore capacity, and at much shorter reach. These facts will greatly challenge the economics of the internet as we know it.

As amazing as the technological achievement of increasing in S.E. has been, it has been no less remarkable that 100 Gb/s digital coherent line cards offer similar or better un-regenerated reach as did 10 Gb/s systems. Although the optical signal-to-noise requirements have become more stringent as Baud rates increase and modulation formats become more complex, the advancements in Forward Error Correction (FEC) and Raman amplifiers have allowed the optical reach to remain longer than 3000km for 100 Gb/s over high quality G.652.D fiber cable. It is widely acknowledged that these distances can no longer be supported as the coherent modulation format moves from quadrature phase shift keying (QPSK) for 100Gb/s to higher order quadrature amplitude modulation (QAM) for 200 and 400 Gb/s and beyond. It has been shown that fiber non-linearity fundamentally limits the ability to increase capacity for a chosen reach. Ref. [3]. For example, the achievable reach with the 16-QAM constellation shown above is approximately four times shorter than QPSK over the same link. In fact it can be shown that, all else being equal, the reach of a coherent link without optical dispersion compensation is a simple function of the spectral efficiency, as shown in Fig. 4.

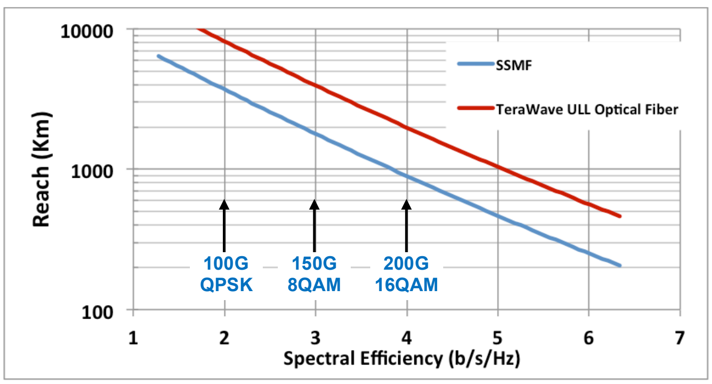


Fig. 4: Calculation of the estimated un-regenerated reach of a coherent system with hybrid-Raman EDFA amplification and 100km spans, using reasonable input to the Gaussian Noise model [4]. Labels show the bit rate for coherent modulation assuming 32 GBaud signaling. Higher capacity results from denser coherent constellations, but these require higher OSNR, which if unfulfilled leads to shorter un-regenerated reach. Advanced fiber can help close the gap. Schemes for achieving 400G using 16-QAM will have essentially the same reach as shown for 200G, since the format does not change.

Technical Limits become Severe Economic Challenges

In short, the slowdown in growth of achievable S.E. means that network operators will be forced to light up fiber pairs more frequently in the future than in the past, since they will fill up the fiber faster as backbone traffic continues to grow at 30 to 50% compound annual growth rates (CAGR). Lighting a new fiber involves a “truck roll” to install and tune up amplifiers in remote huts along the route. Lighting a fiber more frequently also means adding line cards in terminals at a faster rate. A practical means of increasing the capacity for any modulation format and baud rate is to extend DWDM transmission into the L-band. High performance has been obtained with both split C and L bands (Ref. [5]) and single C+L bands (Ref. [6]), including hybrid Raman amplification. This means that new fibers like TeraWave ULL Optical Fiber should have good cabling properties out to 1610nm to support future L-band usage.

Reduced un-regenerated distance for advanced modulation formats implies adding regeneration – crudely speaking, a pair of back-to-back line cards – to the longer routes in the network. Regeneration is a particularly expensive solution, since it is required per wavelength – roughly doubling the cost of adding a wavelength to a fiber pair. Regeneration also consumes the scarce space and power available in a hut: instead of one amplifier card per fiber pair, one requires a regen card for each wavelength regenerated. The cost implications for a network will be shown quantitatively below.

The fundamental technical problem is now clear: Growing capacity means moving to denser modulation formats, which in turn requires higher OSNR in the link, which if not fulfilled will result in shorter un-regenerated reach. We show below that new fibers and advanced amplifiers help by supplying part of this additional OSNR as well as opening up the L-band for additional channels.

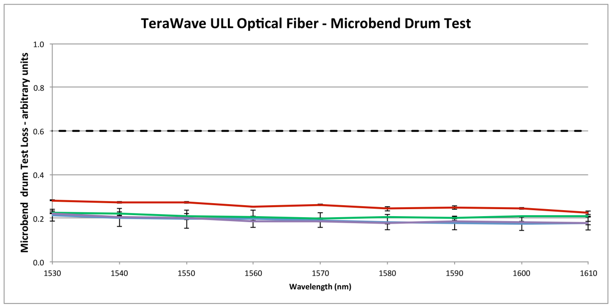
Benefits of Large Effective Area, Ultra-Low Loss Fiber

A fiber that allows the maximum spectral efficiency for a given transmission distance (refer to Fig. 4) can provide great value to a network operator. For example, it is shown in this white paper that deploying an advanced fiber with large effective area and ultra-low loss, such as TeraWaveTM ULL Optical Fiber, helps to both increase the capacity of a cable as well as reduce the cost of lighting a fiber by up to 40 to 80% (in cases where full regeneration is avoided). The ultra-large area of the fiber allows higher launch power without generating non-linear noise on the signal, while the ultra-low loss means that less noise will be added in the amplifier. Both result in higher effective OSNR at the receiver, for any coherent modulation format. Large area fibers also naturally have a higher chromatic dispersion than standard G.652 fibers. Although this was a disadvantage for direct detection systems in the past, it is an advantage in suppressing non-linear distortion with digital coherent receivers. A comparison of typical fiber properties is shown in the table.

	TeraWave ULL Optical Fiber	Installed Base SSMF
ITU-T Category	G.654.B	G.652
1550nm Attenuation (dB/km)	<0.17 (LDV*)	~ 0.22 (typical)
1550nm Effective area (μm^2) typical	125	82
1550nm Chromatic dispersion (ps/nm/km) typical	20.5	17
Cable Cutoff Wavelength (nm)	≤ 1520	≤ 1260
Fiber PMD Link Design Value (ps/√km)	≤ 0.04	≤ 0.2

* LDV refers to the Link Design Value, which quantifies the expected value in installed cable.
Note: The OFS TeraWave Optical Fiber has the same properties as TeraWave ULL Optical Fiber except that the attenuation LDV of the former is <0.19 dB/km.

TeraWave ULL Optical Fiber is a cut-off shifted fiber conforming to ITU G.654.B requirements that is specifically designed to be used in terrestrial cable designs. The TeraWave ULL Optical Fiber waveguide has a trench profile structure (Ref. [7]) that controls macro- and microbending sensitivities across the C and L-bands for excellent cable performance. Therefore transmission benefits described below apply to both C- and L-band. Splicing for TeraWave ULL Optical Fiber splices to itself are about 0.04 dB and TeraWave ULL Optical Fiber to G.652 is about 0.15 dB.



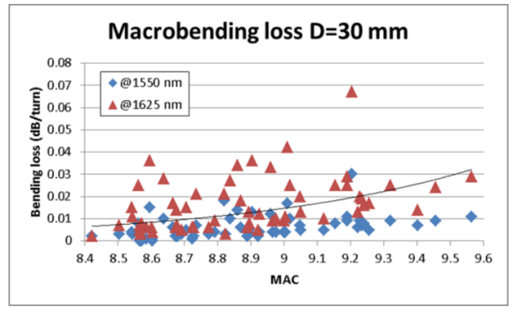


Fig. 5 – (a) Microbending drum test at C+L band wavelengths, (b) measured 30 mm diameter macrobending performance as a function of the fiber MAC factor. These are the key properties behind good cable performance in the field. See Ref. [Peckham] The benefits of the large area fiber over standard fiber can be shown in two ways. Using the Gaussian Noise model, it is possible to derive a figureof-merit Ref [4] to describe the relative benefit in OSNR of one fiber over another with dispersion uncompensated, coherent transport, in the case of EDFA amplification. Note that the figure of merit will change in the case of Raman amplification, giving greater weight to the effective area relative to loss. Ref. [8].

$$FOM = 10\log(\frac{\mathrm{Aeff}}{\mathrm{Aref}}) - (\alpha - \alpha\mathrm{ref})L - 10\log(\frac{\mathrm{Leff}}{\mathrm{Lref}}) + 5\log(\frac{D}{\mathrm{Dref}})$$

The essential physics is evident from the analytic formula. Basically the first term tells us that increasing the effective area (Aeff) of the advanced fiber by 50% over SSMF improves the FOM by 1.8 dB. This is essentially the ability to raise the input launch power without increasing non-linear penalty. Decreasing the span loss directly improves the FOM by the amount in dB from the second term. However the third term is a correction factor which shows an increase non-linear penalty when the loss is reduced, offsetting a part of the gain from the second term. The fourth term shows that raising fiber dispersion improves the FOM by the square root of the ratio of the chromatic dispersion values.

We can also use the full Gaussian noise model, implementing hybrid Raman amplification, and calculate the reach that is possible for a given fiber using different amplifier scenarios and hut spacing [8]. The ratio of achievable un-regenerated reach for different fiber and amplifier combinations is independent of which modulation format is used. For reference, we choose SSMF with EDFA over a range of hut spacing. [This choice of reference is based on the fact that it can be difficult to install Raman on some legacy cables due to high point losses.] For any coherent modulation format, we can calculate how much farther a TeraWave ULL Optical Fiber with different amplification technologies would transmit. The Figure shows that TeraWave ULL Optical Fiber can transmit a coherent format approximately twice as far as SSMF with EDFA amplification for both. The figure shows that hybrid Raman-EDFA and all-Raman amplifiers in conjunction with advanced fiber can greatly extend the reach beyond that obtained with traditional technologies.

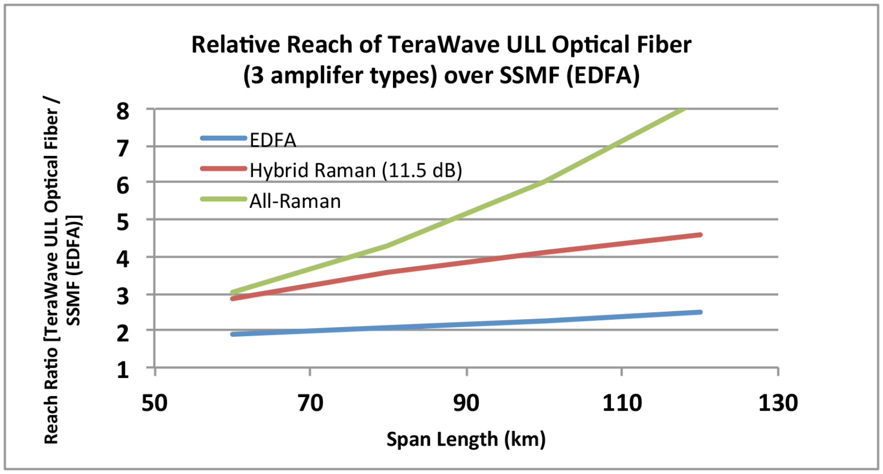


Fig. 6: Ratio of un-regenerated distance using TeraWave ULL Optical Fiber with three amplifier types vs. that obtained using SSMF with EDFA. The ultra-low loss of the TeraWave ULL Optical Fiber has a significantly higher impact when the amplifier spacing is increased. Although not shown, if the legacy SSMF were upgraded to one of the Raman amplifier types, then the result reverts to that of the blue curve, when both fibers have the same amplifier type.

In a different view, we use the GN model to compare the distance to which a given fiber would support increasingly more complex coherent constellations, both simpler and more complex than QPSK and 16-QAM shown above in Fig. 3. The y-axis shows the order of the modulation format that can be supported for the un-regenerated reach on the x-axis. The order of the modulation format or QAM level varies in powers of two. Very high order formats have been used in research, but 16-QAM is the highest commercial format. Common formats are labeled. The black curve shows that SSMF can support very high order modulation formats at short distances, but rapidly falls off. TeraWave ULL Optical Fiber can be seen to support the modulation format for almost twice the distance of SSMF. Another way to look at this data is that for a given transmission distance TeraWave ULL Optical Fiber can support higher spectral efficiency and therefore higher capacity.

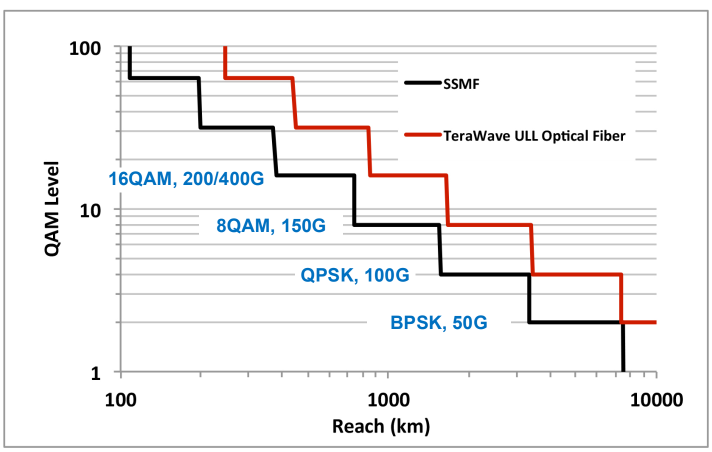


Fig. 7: Red and black curves show the QAM Level that can be supported by TeraWave ULL Optical Fiber and SSMF over a specified un-regenerated distance on the x-axis, where both fibers use hybrid-Raman EDFA. Higher QAM Level indicates higher S.E. Systems companies are beginning to sell flexible format line cards, which will be able to select the highest spectral efficiency possible for the link in question. TeraWave ULL Optical Fiber goes approximately twice as far as installed base SSMF for any coherent modulation format without costly regeneration.

TeraWave ULL Optical Fiber Helps Reduce Cost-per-Bit

One use-case for TeraWave ULL Optical Fibers would be connecting cloud datacenters, where traffic growth is typically close to 50% CAGR, with a target for un-regenerated reach sometimes greater than 4000km. In this scenario, terabits of traffic may be carried immediately, with many fiber pairs lit from "day one." Connections are typically point-to-point connecting hyper-scale datacenters, which serve as giant sinks and sources of data traffic. A second use-case is that of a service provider, where some backbone traffic will be "expressed" between major nodes while other traffic will be optically routed one and off of the backbone at many smaller nodes. Traffic will more typically grow at CAGR near 30%, and the design target for un-regenerated reach might be 2000km. A composite cable may be appropriate in both scenarios, containing a mix of advanced fiber such as TeraWave ULL Optical Fiber and a low loss G.652.D fiber such as AllWave® Low Loss Optical Fiber. A detailed recommendation can be developed in consultation with OFS, tailored to the use-case.

To understand the benefit of TeraWave ULL Optical Fiber for reducing cost-per-bit of transport, we consider two scenarios: one in which TeraWave ULL Optical Fiber is available, and the other where an existing cable of legacy SSMF is used with EDFA in the huts. [This choice of reference is based on the fact that it can be difficult to install Raman on some legacy cables due to high point losses.] In the case of TeraWave ULL Optical Fiber, a flexible format transponder is used to transport the maximum spectral efficiency possible over the required distance. In the case of the SSMF, regeneration would be required to support equal or higher spectral efficiency for the required reach. This scenario is illustrated in Fig. 8.

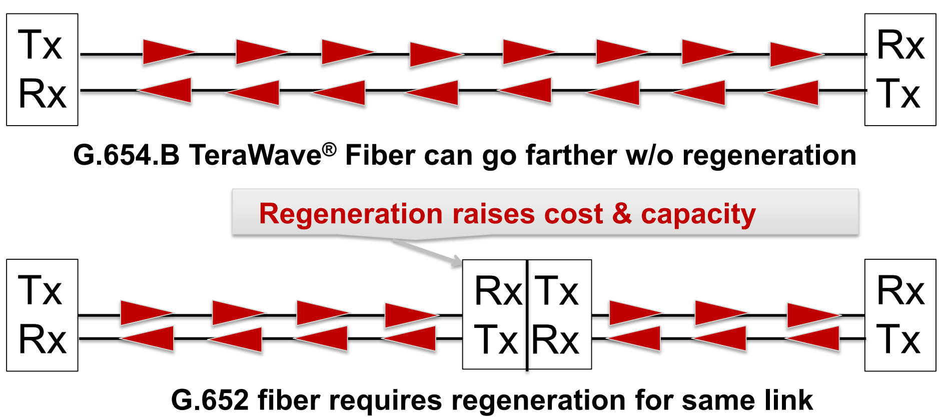


Fig. 8: The top panel shows transport of a coherent format un-regenerated across a target link distance, while the bottom panel shows legacy SSMF requiring regeneration to achieve the same reach. A regenerator is roughly two line cards in a back-to-back configuration, recovering and then re-transmitting the data.

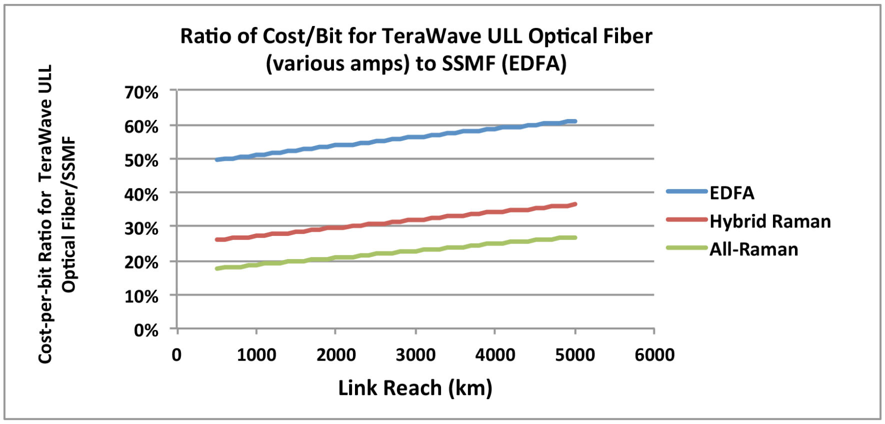


Fig. 9: Links constructed with TeraWave ULL Optical Fiber support a lower cost-per-bit than legacy technologies, by helping reduce the cost of regeneration. The figure shows the ratio of the cost-per-bit for coherent transport comparing TeraWave ULL Optical Fiber vs. legacy SSMF in 100km spans. The calculation includes the cost of a cabled TeraWave ULL Optical Fiber, optical amplifiers and line cards for full C-band for each fiber type, plus a regen for each wavelength in the case of SSMF.

The cost-per-bit of backbone transport using TeraWave ULL Optical Fiber with EDFA ranges from 50% to 60% of the cost-per-bit for the legacy SSMF case, across a range of un-regenerated reach spanning the service provider and cloud content provider scenarios. If Raman amplification is utilized in the case of TeraWave ULL Optical Fiber, the cost-per-bit drops to ~20% to ~35% of that for the legacy fiber with EDFA. (The blue curve also well describes the cost-per-bit reduction whenever the same amplifier type – whether EDFA, hybrid Raman, or all-Raman – is used on both fiber types.)

OFS has also has available a full business case model for advanced fiber deployment, accounting for the net present value of the initial cable investment and the savings over time by lighting fibers and wavelengths more slowly with an advanced fiber compared to the case of SSMF. The TeraWave ULL Optical Fiber requires fewer lit fibers and fewer line cards deployed, compared to the legacy SSMF case, to meet an input traffic growth CAGR. OFS is willing to consult with interested parties to adapt this cost model to your network and investment parameters, such as distribution of un-regenerated distances required, traffic growth CAGR, investment hurdle rate, time horizon of business case, etc.

Summary and Conclusions

Fundamental technical limits will strain the economics of the internet in the near future, because the spectral efficiency of long haul transport cannot keep growing as fast as it did in the first 20 years of DWDM. Higher order coherent formats required to increase capacity require higher OSNR, which if not supplied significantly reduce un-regenerated reach, requiring expensive regeneration. Both traditional service and cloud content providers are encouraged to explore the benefits of using advanced fiber such as TeraWave ULL Optical Fiber to support higher spectral efficiencies at longer un-regenerated distances, to help reduce cost-per-bit of transport.

Please contact your sales representative to consult with OFS on your long-haul fiber questions.

References

[1] P. Winzer, “Spatial Multiplexing in Fiber Optics: The 10x Scaling of Metro/Core Capacities,” Bell Labs Tech. J., vol. 19, p 22, 2014.
[2] K. Roberts, “Heading Off the Capacity Crunch,” Gazettabyte May 30, 2012 http://www.gazettabyte.com/home/tag/kim-roberts.
[3] R-J Essiambre, et al., “Capacity Limits of information transport in fiber-optic networks,” Phys. Rev. Lett., vol. 101, 163901 (2008).
[4] A. Carena et al., “Novel figure of merit to compare fibers in coherent detection systems with uncompensated links”. Optics Express 20(1), 2012.
[5] J.X. Cai, et al., “49.3 Tb/s Transmission Over 9100 km Using C+L EDFA and 54 Tb/s Transmission Over 9150 km Using Hybrid-Raman EDFA,” J. Lightwave Techn. vol. 33, 2724, (2015).
[6] B.Y Zhu, et al., “34.6 Tb/s (173x 256Gb/s) Single-band Transmission over 2400km Fiber using Complementary Raman/EDFA,” OFC2016, paper Tu3A.1, 2016.
[7] D. Peckham, et al., “Optimization of Large Area, Low Loss Fiber Designs for C+L Band Transmission,” OFC 2016, paper Tu3A.1.
[8] K. Balemarthy, R. Lingle Jr., “Reach Comparison of Next Generation Optical Fibers with EDFA/Raman Amplification,” ECOC 2013, paper We.4.D.1.