Is Your Network Ready for Raman Amplifiers?

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RAMAN AMPLIFICATION: WHY NOW

While distributed Raman amplifiers have been commercially available for 15 years, their role within dense wavelength-division multiplexing (DWDM) networks is expected to increase beyond their typical application in long-haul networks. This increased adoption is being driven by the huge bandwidth demand that network operators are facing. In fact, Raman amplifiers have proven beneficial in all of the technology choices that can be used to deploy 100G and above.

Meeting the Need for Higher Transmission Capacity

Network designers have several options to meet the need for higher transmission capacity. For instance, one obvious solution is to extend beyond the C-band into the L-band. However, this extension is far from trivial, given that the C- and L-bands use different amplifiers and reconfigurable optical add/drop multiplexers (ROADMs), which will increase costs. Furthermore, C-/L-band coupling loss, non-linear interaction between C- and L-band channels, and lower-performing L-band erbium-doped fiber amplifiers (EDFAs) negatively impact the optical signal-to-noise ratio (OSNR).

Another option is to increase the symbol rate. Today, the typical symbol rate is around 30 GBd, which translates into 120 Gbit/s for the widely deployed dual-polarization quadrature phase-shift keying (DP-QPSK) modulation format. Over the next two years, there will be opportunities to increase the rate to ~45 GBd or higher. However, this increase will require faster electronics, including higher-bandwidth analog electronics, optical modulators, receivers and digital signal processor (DSP) chips that operate and run algorithms at a higher baud rate. The increase in symbol rate requires a higher OSNR, which limits the maximum transmission distance compared to lower-rate signals.

A third option for increasing capacity is to increase spectral efficiency, either through the use of higher modulation formats (such as 16-QAM) that encode a higher number of bits per symbol, or by maintaining the same modulation format and reducing the spacing between channels, or a combination of both. Higher-order modulation formats require higher OSNR, whereas narrower frequency spacing between channels has an associated transmission penalty that must be compensated for with higher OSNR.

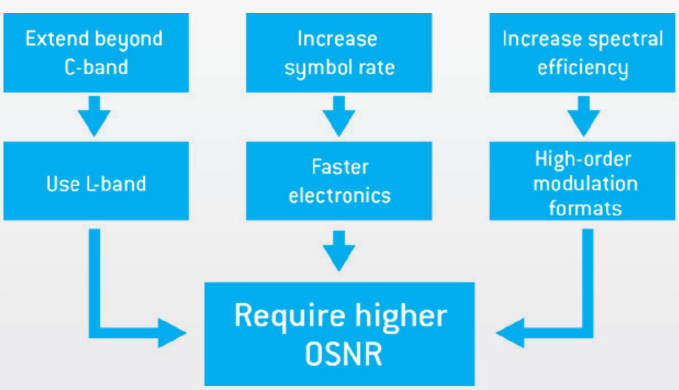

Figure 1. The paths to higher transmission capacity all require higher OSNR

In any of these cases, network designers will require a higher OSNR in order to transmit higher capacity over practical distances on a given network without requiring expensive opto-electronic regeneration.

As detailed below, Raman amplifiers provide the higher OSNR required to increase capacity in all three options discussed above.

How Distributed Raman Amplification Works

Distributed Raman amplification uses the network fiber as the gain medium, as opposed to discrete amplifiers such as EDFAs or discrete Raman amplifiers, where amplification takes place inside the amplifier black box.

For instance, in a typical fiber span with booster EDFAs, the signal first passes through a booster EDFA before passing through a fiber span and ultimately being amplified by another EDFA. The power of a signal propagating through the fiber decreases continuously over the distance between the two amplifier locations, as shown in Figure 2.

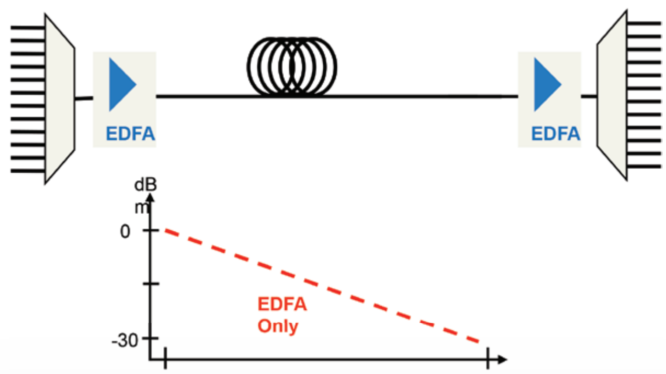

Figure 2. Signal power vs. distance with EDFA only

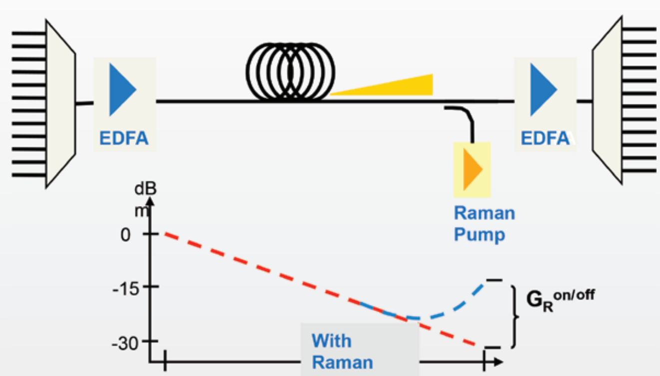

Figure 3. Signal power vs. distance with EDFA and Raman amplifier

By adding a distributed Raman amplifier to this span, signal power loss can be decreased, and the signal power does not drop to the low levels obtained in the case of amplification by EDFAs only. The commonly deployed counter-propagating Raman amplifier consists of one or more Raman pump lasers and a wavelength combiner, such that the Raman pump wavelengths are transmitted into the fiber in the opposite direction of the signal. As the signal propagates along the fiber, it will be attenuated, but as it moves along toward the fiber end where the Raman pump is located, it will start to experience some gain from the Raman pump wavelength, as displayed in Figure 3. In this configuration, distributed Raman amplifiers are typically used to complement EDFAs, although the Raman amplifier could also be used by itself. The end result: the higher power in the signal along the fiber increases OSNR. There are several ways that this increase in OSNR can be leveraged in a link, including:

- To enable longer fiber spans than would be obtained with EDFAs alone.
- To obtain higher capacity via higher order modulation formats and higher spectral efficiency.
- To extend the total link distance, assuming the link has multiple fiber spans.
- To enhance the operating margins, even if the EDFA is adequate in marginally supporting a given link.

EDFAs vs. Distributed Raman Amplifiers

Network designers must also consider differences between EDFAs and Raman amplifiers. One major difference involves the gain medium. With the EDFA, the erbium fiber is contained within the amplifier card or shelf provided by a DWDM vendor. In the case of the Raman amplifier, the gain is actually obtained from the transmission fiber itself.

Another difference is the use of pump wavelengths. With an EDFA, the gain spectrum is determined by the erbium-doped fiber, with fixed-wavelength pump lasers at 980 nm or 1480 nm. With a Raman amplifier, there is a choice of different pump wavelengths, which in turn determine the gain spectrum.

The third major difference derives from the use of the fiber as the amplification medium by distributed Raman amplifiers, thereby effectively maintaining higher signal power through the fiber and yielding higher OSNR.

On the other hand, the EDFA also has higher gain and higher output power than the Raman, and delivers the highest wall-plug efficiency in terms of optical output power per unit of electrical power consumed of all the available amplification technologies. The gain efficiency also results in lower-cost-per-unit gain. These advantages make the EDFA the default amplifier for use in DWDM transmission. Nevertheless, the Raman amplifier complements the EDFA very well, because the Raman provides an improvement in performance that is not obtained with EDFAs alone.

As an example, Figure 4 shows the effect of Raman amplification on a simple multispan link with 23 dB loss per span compensated by 23 dB of amplification. In one case, each span loss is compensated with an EDFA, whereas in the second case, the gain is divided between the distributed Raman amplifier and the EDFA. In the case of the hybrid EDFA/Raman amplification, the OSNR curve has shifted upwards towards higher OSNR values. The impact on the link is an increase in OSNR for the same span number, or conversely, a much larger span number attained with the same OSNR.

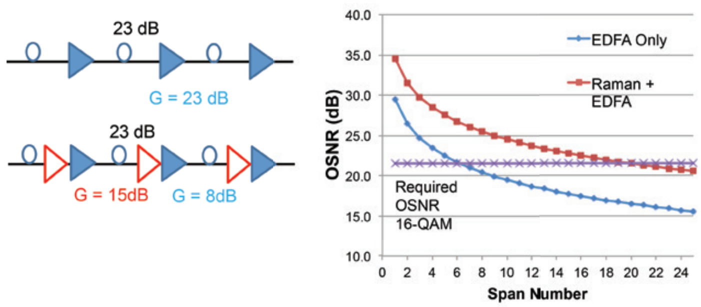

Figure 4. The effect of Raman amplifiers added to a multispan link

Figure 4 also shows that, assuming the required OSNR at 16-QAM would be 21 dB, and accounting for some transmission penalties, the EDFA-only configuration would be able to support a maximum of seven spans, whereas the EDFA/Raman configuration would increase the maximum number of spans to about 20. By incorporating Raman amplifiers, the link becomes more robust, with more margin available for future repairs or changes along the link.

DESIGN CONSIDERATIONS

Finding the Needed Gain

A major consideration with Raman amplification is optimizing the gain to be obtained. Gain depends heavily on fiber types, and in order to understand this dependency, the first factor to be taken into consideration is what drives gain. With a Raman system, the gain obtained fundamentally depends on one thing: the pump power density. Pump power density, in turn, is directly dependent on the effective area of the fiber. For this reason, knowing the fiber type and its characteristics is critical. Each type of fiber has a different effective area, and therefore yields a different gain.

In other words, to optimize gain, network designers and planners must know what types of fiber are in use. Many will start with fiber databases, which are accurate and good places to begin. However, over time fiber spans change. Some of the fiber deployed in the late 1990s might have been replaced, and oftentimes, the fiber information gets lost after the original fiber owner has gone through mergers and acquisitions. As a result, the fiber databases become less reliable.

Designers are confronted with a dilemma: how do they identify the type of fiber in a deployed span if the initial data from a fiber database is no longer 100% reliable?

Many use chromatic dispersion (CD) analysis, because there is a signature for each fiber. Indeed, a CD analyzer will generate parameters such as CD, zero-dispersion wavelength (lambda-zero) and CD slope, which provide sufficient information to identify the fiber type, and therefore support design efforts.

Finding Fiber Types

Figure 5 lists several fiber types with their typical parameters. As shown, these fiber types can vary widely depending on the fiber. But other values are close: note the close lambda-zero values for dispersion-shifted and Corning second-generation leaf (also referred to by some as E-LEAF) fibers, although with variation on dispersion and slope. By combining these three parameters, it is possible to accurately identify the fiber type.

Fiber Type	Lambda Zero	Dispersion @ 1550 ps/(nm*km)	Slope @ 1550 nm (ps/(nm*nm)*km)
Standard singlemode	1300 nm to 1324 nm	16 to 18 (17 typical)	~0.056
Corning LS	~1570	−3.5 to −0.1 (−1.4 typical)	~0.07
Dispersion-shifted	~1550	~ 0	~0.07
True-wave classic	~1500	0.8 to 4.6 (2 typical)	~0.06
True-wave plus	~1530	1.3 to 5.8	
True-wave reduced slope	~1460	2.6 to 6 (4 typical)	< 0.05 (0.045 typical)
Corning E-LEAF	~1500	2 to 6 (4 typical)	~0.08
Alcatel TeraLight	~1440	5.5 to 9.5 (8 typical)	~0.058
True-wave reach	~1405	5.5 to 8.9 (7 to 8 typical)	< 0.45

Figure 5. Values characterizing different fiber types

If there is a mix of fibers in the span, more investigation will be needed. From this research, along with the total dispersion measurement and other parameters gained through trial and error, the types of fiber and combinations on the span can be determined.

Through identification of the fiber types, it is possible to fulfill a key requirement for the effective use of Raman amplifiers: knowing the fiber's gain and the required Raman pump power.

Finding Pump Attenuation

Once the fiber types have been identified, the other question that must answered is how far the pump reaches. To answer this question, the fiber attenuation must be observed at the pump wavelength.

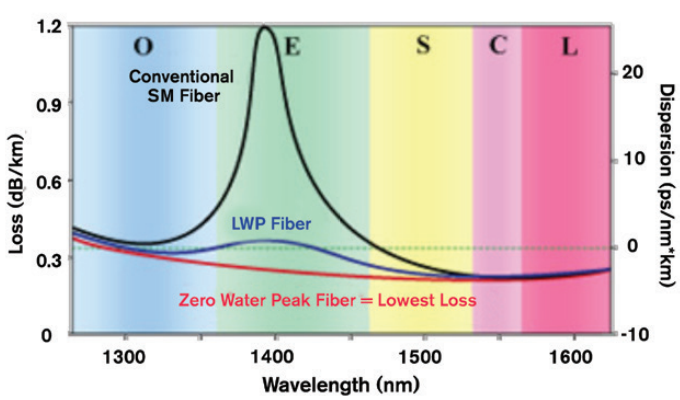

Figure 6. Attenuation at the Raman pump wavelength at 1430 nm depends heavily on the fiber type and the presence of water absorption peak

If the system is operating in the C-band, the Raman pumps can be in the range of 1430 nm to 1470 nm. The presence or absence of water absorption peak around 1383 nm can induce a high attenuation around these wavelengths. As an example, Figure 6 shows that fibers with zero water peak will have a loss of about 0.3 dB/km at 1430 nm, while conventional singlemode fiber might exhibit about 0.6 dB/km loss at that same wavelength. These differences have a huge impact on the Raman pump reach.

Impact on System Reach

Consider an example where fiber A is a newer fiber without water absorption peak with 0.24 dB/km attenuation at 1450 nm, whereas fiber B is an old fiber of the same type as fiber A, and exhibits 0.33 dB/km loss at 1450 nm. Based on 1 dB loss per connector, the impact of the higher loss would be a 28% shorter link distance for fiber B than fiber A. Therefore, an error made in the attenuation assumption at the pump wavelength could have a high impact on the overall performance of the Raman system. This justifies measuring the fiber loss at 1430 nm with an OTDR.

DEPLOYMENT CONSIDERATIONS

Keep Fiber Clean

In addition to the previously explored design considerations related to Raman amplification, there are also several key deployment precautions that must be keep in mind.

With Raman amplification, the equipment will need to be connected to the network fiber with minimum connection loss. During the connection process, the fiber and connectors must be kept clean, because dirt, contamination and misalignment will adversely impact fiber attenuation.

Connection loss is caused by a number of factors, such as multiple connectors and patch panels between the DWDM equipment and the network fiber where the Raman gain is obtained, contaminated connectors and fiber bends. Also, the epoxy in old connectors can degrade, in which case the fibers may cease to mate perfectly.

Connector Loss

The impact of connection loss can be significant. In Figure 7, the plot shows the reduction in Raman gain due to different connector losses when the connector is located very close to the Raman pump. The three curves (green, red and blue) correspond to different fiber attenuation levels at 1550 nm. In this example, which uses a Raman amplifier with a net gain of 15 dB, a 1 dB connection loss can result in a 4 dB gain reduction, and a 2 dB connection loss increases the reduction in Raman gain to 7 dB, which is substantial.

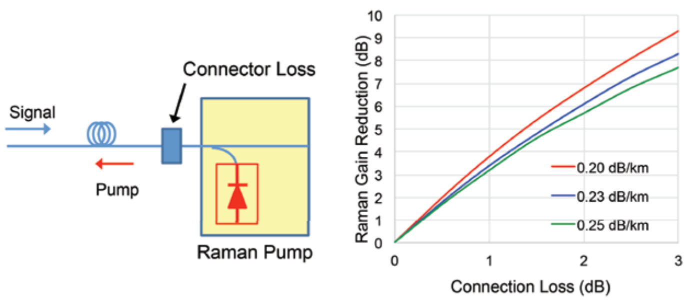

Figure 7. Impact of connection loss on Raman gain

Location of the Loss Element

In addition to the magnitude of the loss matter, its location is also critical. Figure 8 displays the Raman gain reduction for different positions of the loss element at 0 km, 5 km, 10 km and 20 km away from the Raman pump. The dependence on the magnitude of the connection loss is also shown. Figure 8 reveals that the Raman gain reduction is lower if the connection loss is located further away from the Raman pump. This is because most of the Raman gain occurs close to the Raman pump.

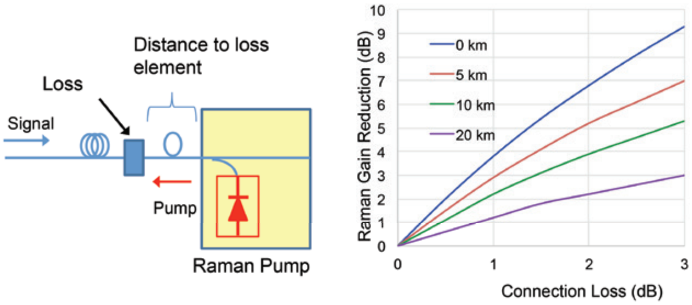

Figure 8. Raman gain reduction as a function of the connection loss, and the distance between the Raman pump and the loss element (0 km, 5 km, 10 km and 20 km)

In other words, the same loss located beyond the effective length of the fiber has minimal contribution to gain reduction. Most of the gain obtained through distributed Raman amplification is obtained in the region of the effective length of the fiber, which is in the ~20 km range.

More Powerful Pumps?

Given these loss issues, it might be logical to simply use more powerful pumps, and pump the fiber harder. But, that would be a mistake. If the loss is due to discrete loss, or imperfect or contaminated fiber, a concentration of light will be produced in certain areas of the connector endface—resulting in permanent damage to that connector, the DWDM equipment and the patch panels.

The connector would have to be re-spliced, either in a patch panel on the site, or on the DWDM equipment. Apart from the associated cost, the project would be delayed due to needed repairs. However, the DWDM equipment often includes mechanisms to prevent excess power use and alert technicians about the problem.

Back Reflections

Another problem that may occur from imperfect connections is the presence of air gaps from aging connectors or dirt wedged between connector endfaces, which generate back reflections. Back reflections are always a problem, even with EDFA links, but have a worse impact with Raman amplifiers, because any back-reflected signal along the fiber span will be amplified by the Raman amplifier, thus amplifying the signal in both directions. This does not happen with an EDFA amplifier, where this back-reflected signal would actually see attenuation. In the case of Raman, it will see gain. If there is a second backreflection point, the result is a ghost signal that propagates along with the main signal, leading to multipath interference (MPI). Consequently, MPI gives rise to a crosstalk signal at this point and cannot be eliminated. Thus, it will propagate toward the receiver, which will be impacted by this double backreflection, as displayed in Figure 9.

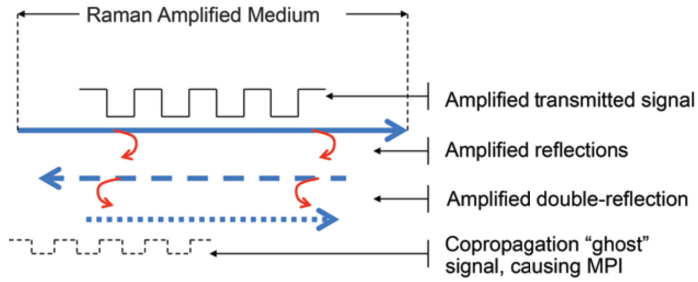

Figure 9. Impact of MPI

This impact was quantified in a previous publication (Tibuleac et al., NFOEC 2005). The noise figure (NF) of the amplifier was obtained as the most relevant characteristic of the amplifier affecting the signal quality. The NF is typically determined by the amplified-spontaneous-emission (ASE) noise, with an extended definition provided in Figure 10 below to include the impact of double backreflections in an equivalent NF parameter.

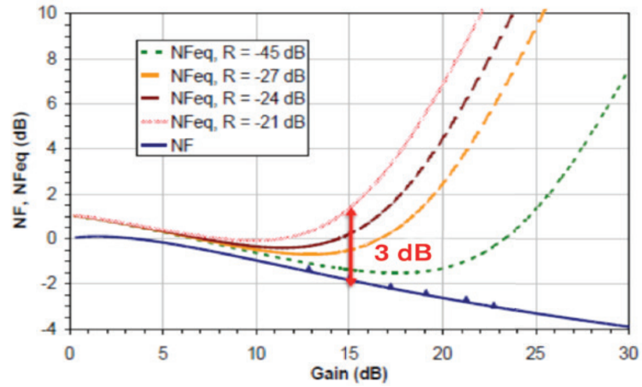

Figure 10. Impact of connector backreflection on NF

Figure 10 shows different levels of reflection for a single connector and the resulting equivalent NF. The dark-blue downward slope on the NF curve represents no back reflection, and keeps dropping as the gain is increased. Taking this as a reference, the other curves show the equivalent NF at the higher reflection values. If the reflection from the connector is as high as −21 dB, there is a 3 dB increase in the equivalent NF, and this can have a significant impact on the OSNR and system reach.

How to Address Backreflection

Technicians should start by correctly manipulating a fiber inspection probe. It is important to ensure that the ferrule is placed directly in the center of the probe, and that the probe is set at the correct focus for the analysis. With Raman amplification, the power is high, especially in the first connector after the pump. Even the smallest defect or speck of dirt on the connector or fiber will have a major impact. Therefore, it is critical to perform accurate fiber inspection; for instance, using the FIP-400B family of inspection probes.

CONCLUSION AND RECOMMENDATIONS

Raman gain and overall Raman performance estimation is an important part of network planning, and knowledge of the fiber type is critical for proper modeling of a DWDM network. Chromatic dispersion testing can help in the event that the fiber type is unknown.

For pump wavelengths that are approximately 1430 nm to 1450 nm, the attenuation level in the fiber can vary based on fiber type. Even within the same fiber type, and depending on the date of manufacture, fibers may have different attenuation profiles. Therefore, it is critical to measure attenuation at these wavelengths using an OTDR.

Fiber inspection probes are needed to ensure that clean connector endfaces are used for the transmission of high-power Raman pumps into the network fiber. The absorption and scattering associated with contaminated connectors can either damage the network equipment or prevent Raman amplifiers from being turned on by safety mechanisms implemented in the DWDM equipment. Technicians must therefore exercise care during implementation, and for this reason it is extremely important to include fiber and connector inspections in the work process.

High reflections in a network can generate MPI, which presents a risk to signal integrity. Inspection probes are useful in this regard as well.

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WHITEPAPER072.1AN

Printed in Canada 16/04