PUSHING THE REACH OF REPEATERLESS TRANSMISSION SYSTEMS

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Abstract: Technologies that enhance the maximum obtainable capacity and reach of repeaterless systems are reviewed. It is shown that 64x10 Gbit/s can be transmitted over a segment loss > 70 dB using simple, commercially available technology. After considering the trade off between wet plant and terminal complexity, it is concluded that increasing wet plant complexity is the preferred option for the design of new undersea repeaterless systems.

1. INTRODUCTION

Repeaterless submarine systems occupy an important niche in the telecommunications infrastructure by effectively connecting stations separated by a few hundreds of kilometers without the use of periodic in-line amplification, power-feed equipment, and related expensive maintenance of the submerged electro-optical equipment [1,2]. Even though the terminals for repeaterless systems can be fairly complex, involving high-power amplifiers, Raman pumps, and pumps for Remote Optically Pumped Amplifiers (ROPA) repeaterless systems can offer lower total system cost compared to traditional repeatered or light repeatered systems [3]. Typical applications are coastal festoons, island hopping, and links between oil platforms.

The critical design parameters for repeaterless systems are launch power, path loss, receiver sensitivity, and path gain. In recent years, we have seen some improvement in fiber loss, but the major advances enabling longer reach and higher capacity have been in the areas of modulation format and pump laser technology. Advances in commercialized terminal and remote pumping equipment have given the industry many decibels (dB) of additional margin between transmitter and receiver that can be used to cover longer spans, higher bit rates, or more channels. On the other hand, complex system designs that take full advantage of new technologies are expensive, and repeaterless systems designed near the limits of feasibility cost more (and are less robust) than systems built with undersea repeaters. For example, there are few (if any) deployed repeaterless systems using a separate fiber path for optically pumping a ROPA [4], even though that technology allows greater reach for some system capacities.

This paper reviews some of recent technological advances that are used in the current generation of repeaterless systems. Defined are the advantages gained from each type of system topology, before the trade off between wet plant and dry complexity is discussed. The paper focuses on readily available and practical technologies.

2. TOPOLOGIES

This paper looks at five basic types of repeaterless system. The schematics for these types are shown in Figure 1. They are arranged in ascending order of cost, complexity, and maximum system reach. With all of these configurations, the signal power may be limited by inter-channel and intra-channel nonlinear effects that degrade performance at channel power levels well below those at which stimulate Brillouin scattering (SBS) is observed. Inter-channel Raman crosstalk limits useable bandwidth and diminishes reach at higher capacities.

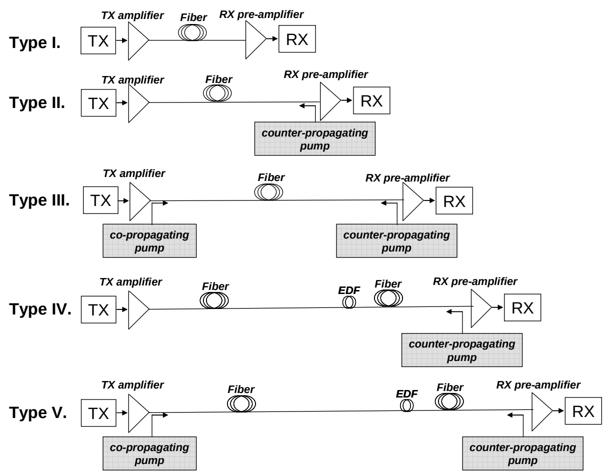

Figure 1. Main topologies used repeaterless design. The types are arranged in order of increasing complexity. Type I has the shortest reach and Type V has the longest reach.

Type II systems introduce a counter-propagating Raman pump at the receiver terminal to provide additional gain to the signal by Raman gain in the fiber. Using the simplest form of Raman pump (single wavelength), about 19 dB gain can be achieved in a fiber with A_{eff} = ~80μm^2. The main limitation of this configuration is reflected Raman noise and, at very high pump powers, Raman lasing. More sophisticated Raman amplifier pumping schemes such as higher-order pumping can be used to enhance the reach of this type of system. Typically Raman pump wavelengths of ~1450nm are used to provide flat gain near the center of the C-band.

The next level of complexity is achieved by introducing a co-propagating Raman pump to the transmit terminal. See Figure 1, system type III. The forward pump makes possible a higher ratio of received optical power to path average power, but it adds noise from the Raman amplifier.

System type IV adds another level of complexity with the introduction of the Remote Optically Pumped Amplifier (ROPA). This ROPA is a length of Erbium doped fiber (EDF) optically pumped from the receive terminal using a 1480 nm laser. In its simplest form, a ROPA can be a section of EDF placed in a splice box. Almost always, a ROPA is closer to the receiver than to the transmitter, creating an asymmetry in the wet plant path design that complicates span manufacture. Depending on the type and length of EDF and pump power reaching the ROPA, a ROPA can provide around 18 dB of gain or more. A consequence of using the 1480nm pump is that the ROPA pump power generates Raman gain in the signal band in fiber between the receive terminal and the ROPA. The pump power required to achieve a given total gain in a ROPA-based design is reduced relative the pump power needed in type II systems.

An important limitation for type IV systems is the location of the ROPA within the span. Ultimately the available pump power determines the maximum distance that the ROPA can be placed from the receive terminal. Higher order counter-propagating pumps can be used to extend this distance. At the cost of additional complexity, performance can be enhanced by adding an input isolators at the ROPA and coupling of the counter-propagating Raman pump so that it propagates through the ROPA in a co-propagating direction. In the case of the former it improves noise figure and prevents ROPA lasing and the latter can significantly improve the ROPA noise figure.

Topology type V adds a co-propagating Raman pump to the configuration in type IV. Co-propagating Raman pumping in this configuration generally brings a relatively small increase in system reach compared to the amount of complexity added to the terminals.

3. TECHNOLOGIES

Whilst the repeaterless system topologies have not evolved greatly in recent years, certain aspects of wet and dry plant technology have made significant strides forward. This section reviews some of the important advances in technology that are commercially available.

3.1. Advances in fiber technology:

The simplest method of increasing system reach is to use low attenuation fibers. Commercially available fibers designed for repeaterless applications currently have losses as low as 0.163 dB/km. Compared to conventional undersea fibers, which have a typical attenuation of ~0.21 dB, the latest generation of fibers reduce the loss of a 400 km link by 18.8 dB. Such fibers have relatively high dispersion at 1550 nm, which must to be compensated at the terminals. Fibers with less dispersion come at the expense of increased attenuation. Suitable fibers for creating efficient in-segment dispersion compensation are not currently used, due to their small effective area and high attenuation.

The fiber's effective area is also an important design consideration. Small effective area fibers yield higher Raman gain at fixed power levels but cause larger nonlinear transmission penalties. Likewise, large effective area fibers lead to lower nonlinear transmission impairments but also reduced Raman efficiency. In a laboratory environment, it is possible to achieve the most desirable combination of large effective area fiber at the transmit end of the link and small effective area at the receive end when counter propagating Raman pumps are used. However, this fiber asymmetry complicates the manufacture of the cable and therefore using a moderate effective area fiber for the entire link is generally more cost effective.

3.2. Transponders

Advanced modulation formats such as Differential Phase Shift Keying (DPSK) with balanced detection can also extend the reach of repeaterless systems. Compared to standard RZ modulation this modulation format has a 3 dB OSNR advantage. In addition, because SBS is less likely to limit channel launch power with this modulation format, wavelength dithering is not required. Advancements in Forward Error Correction (FEC) can also be used to extend reach, though the benefit is modest for recent enhancements in FEC (5 km more reach for 1 dB increase in Net Effective Coding gain).

3.3. Terminal amplifiers

Driven by the advances in commercially available fiber with large effective area and the demand for high capacity, high power terminal amplifiers are readily available. Often designed with two stages and using rare earth doped combinations such as Erbium-Ytterbium, output powers of up to 2W are commonplace. However, this brings the additional complexity and cost of safety systems required for field deployment of commercial equipment generating such high optical powers. Progress in amplifier design has also led to receive pre-amplifiers that can deliver a low noise figure at extremely low channel powers.

3.4. Raman amplification

Modern developments in the field of Raman amplification have resulted in commercially available pumps using higher-order pumping schemes [5,6]. Such schemes use a series of (shorter) wavelength pumps to either extend the Raman gain further into the span or flatten the gain across a wider bandwidth. Recent laboratory experiments have demonstrated ~2.7 dB improvement in performance by using a sixth order pumping scheme [5]. However, the commercially available second and third order pumping schemes bring more modest improvement in system performance (1.8 dB improvement for third order pumping) [5]. It should be noted that fibers with a relatively long single mode cut-off wavelength will cause higher order pumping schemes to operate with reduced efficiency due to the multimode propagation of the shorter wavelengths.

4. REPEATERLESS SYSTEM REACH

Using the technologies and topologies described above, simulations were performed to estimate the maximum reach of the latest generation of 10 Gbit/s channels for a range of capacities. The simulations assumed the RZ-DPSK modulation format, and fiber with an effective area (A_{eff}) of ~80μm^2. All the simulations are performed using a single wavelength Raman pump with optimized launch power where applicable. For systems without a ROPA a pump wavelength of 1450nm was used. 1480nm was used for systems with a ROPA. The results are shown in Figure 2.

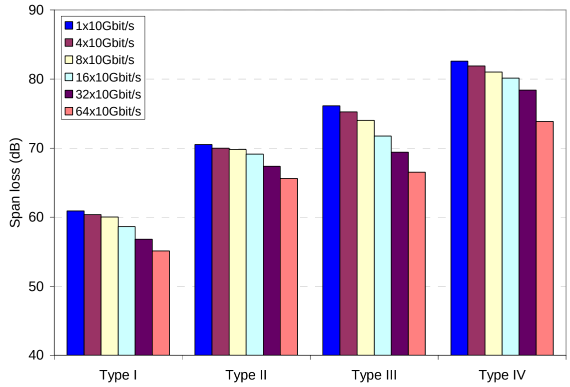

Figure 2: System reach of various repeaterless topologies shown for a range of capacities. The simulations assumed moderate effective area fiber (80μm^2), RZ-DPSK modulation format and single wavelength Raman pumps where applicable.

Type I systems are suitable for links up to ~61 dB. Type II systems increase reach by around 10 dB (~50 km) relative to Type I. This could be increased further by increasing the order of the counter-propagating Raman pump. Addition of the co-propagating Raman pump (type III systems) expands reach by an extra 5.5 dB for single channel transmission. It can be seen that the improvement brought by introducing the co-propagating pump was around half of the improvement observed when the counter-propagating pump was added. Type IV systems bring around 22 dB of improvement relative to type I systems, and around 12 dB relative to type II systems. Type IV system could also benefit from higher-order counter-propagating pumps. This demonstrates that by using a ROPA and single wavelength 1480nm Raman pump, it is possible to transmit 64x10 Gbit/s over a link with ~73 dB of loss. Single channel transmission can be achieved for losses in excess of 80 dB. System reach can be extended further by adding a co-propagating pump (type V system). Typically 1-2 dB extra loss, relative to type IV systems, can be tolerated depending on channel loading.

Before migrating from a type II system to a type III system, it is important to know whether a second-order counter propagating pump in a type II system is more efficient than using first-order co-propagating and counter-propagating pumps. The possible 5.5 dB improvement in performance brought by the co-propagating pump added for the type III system is far in excess of the < 1.8 dB that a second-order counter-propagating pump scheme would bring. However, a forward pumping unit is likely to cost more than adding a second wavelength in the counter-propagating direction.

5. WET PLANT COMPLEXITY VS. DRY PLANT COMPLEXITY

For a specified distance and capacity, there is usually more than one choice of topology that allows successful implementation. This is evident in Figure 2. In general, the more complex terminal topologies yields more expensive solutions, but there may be circumstances that dictate against use of a ROPA. For example, a customer may not be willing to accept very high pump powers in their terminal (safety). Or, if the fiber in the cable is chosen for minimum loss, the extra dispersion compensation equipment needed in the terminal could add too much to system cost. The ROPA gives the biggest increase in length and capacity for the cost, but it also complicates system maintenance somewhat. The upgrade path planned for the system can also affect the topology choice, as can questions of whether the system can be taken out of service to implement an upgrade.

6. CONCLUSION

Some of the main commercially available technologies used to extend the reach of repeaterless systems have been reviewed. Using these technologies, the potential reach as a function of capacity has been detailed. The results show that high capacity transmission can be achieved for link losses greater than 70 dB, using fairly simple terminal equipment. Increasing wet plant complexity offers the greatest enhancement in performance but is only practical for new build systems. Increased dry plant complexity such as advanced modulation formats and higher order Raman pumping bring the most benefit to the upgrading of existing system where costs of altering the wet plant become prohibitive. For ultimate reach, all the elements of the wet plant and dry plant technology need to be combined, and the cost becomes comparable to that of a repeatered solution.

7. REFERENCES

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