Current Trends in Unrepeatered Systems

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Abstract: The current trends in unrepeatered system design that have led to the achievement of 100 Gb/s transmission over a 100-dB fiber span are reviewed. Future steps in improving the technology are discussed.

1. INTRODUCTION

Unrepeatered (UR) transmission systems are characterized by an extremely long fiber span with no in-line electrically powered elements between the terminals and are typically deployed in submarine environments. The relative performance of UR links is constrained by four main factors: fiber properties, transponder technology, Raman amplification, and remote optically-pumped amplifier (ROPA) design and location [1], [2]. Advancements in all these areas has resulted in new records for channel capacity and reach. Experiments of high spectral bandwidth have demonstrated a capacity of 15 Tb/s over 65 nm in a 68-dB span [3]. Experiments in reach have demonstrated 100 Gb/s transmission over a 100-dB span [4]. This paper will review the technologies and limitations in UR system design.

2. ULTRA-LOW LOSS AND LARGE EFFECTIVE AREA FIBER

The development of pure silica core (PSC) fibers has resulted in lower attenuation and larger effective core area (A_{eff}) and is a critical advancement for all optical communications' links. These ITU-T G.654.B and G.654.D compliant fibers are now manufactured with a mode field diameter up to 14.0 μm (153 μm^2 A_{eff}) by several companies and with an attenuation specification near 0.155 dB/km [5].

In UR spans that are 500 km long, each 0.002 dB/km reduction in fiber attenuation reduces the span loss by 1.0 dB. In addition to the lower span loss, the efficiency of Raman pumping is also improved with lower fiber attenuation [2]. A larger A_{eff} enables a higher transmit signal power in the fiber where the optimum power is the point where the linear increase in optical signal-to-noise ratio (OSNR) is balanced by nonlinear penalties. The optimum power in the fiber scales with A_{eff} such that a 153 μm^2 fiber can have a power in the line fiber that is 2.8 dB [$=10*\log_{10}(153/80)$] higher than standard single-mode fiber (SSMF). However, Raman gain in dB scales inversely with A_{eff} such that 1.9x (= 153/80) higher pump powers (mW) are required in these fibers to achieve the same Raman amplification as in 80 μm^2 PSC fiber. PSC fibers with intermediate A_{eff} values in the 110 to 130 μm^2 range may be a better choice in many cases based on available Raman pump power, capacity requirements and/or cost.

3. TRANSPONDER TECHNOLOGY

High spectral efficiency coherent transponders supported by advanced digital signal processing (DSP) are widely used in optical communications links. The span loss that can be supported depends not only on the bit rate and receive OSNR threshold, but also on the optimum power in the line fiber.

The optimum transmit power for 100 Gb/s PM-QPSK into 85 μm^2 PSC fiber is about +14.5 dBm per channel (without co-propagating Raman amplification). The optimum transmit power for 200 Gb/s PM-16QAM is about +10 dBm for the same fiber. Additionally, 16QAM (at the same baud rate) requires about 7.3 dB higher OSNR. Thus, 16QAM can be transmitted over a span that is 11.8 dB less loss than QPSK while only providing twice (+3 dB) the capacity, a net penalty of 8.8 dB in the capacity x span length metric. Therefore, in UR links, the best capacity x length product is currently achieved using the PM-QPSK or PM-BPSK modulation format and higher spectral efficiency formats should only be used if the capacity is limited by available spectral bandwidth (or factors other than the capacity x length metric).

Another interesting facet of UR performance is that the optimum power in the line fiber is mostly limited by intra-channel nonlinear penalties. In other words, the optimum power decreases only slightly for multiple channels compared to a single channel. This suggests that DSP techniques to compensate for nonlinear penalties may play a more important role in UR links than in multi-span links where cross-channel penalties tend to dominate. The reason is that DSP techniques to mitigate nonlinear penalties are much more amenable to compensation of intra-channel effects.

4. RAMAN AMPLIFICATION

Co-propagating (Fwd) and counter-propagating (Bkwd) Raman amplification is an important requirement for optimizing UR performance. Higher amplification within the line fiber generally improves OSNR up to the point where penalties due to multi-path interference (MPI) and other penalties start to dominate [2].

The optimum signal power in the line fiber is lower with Fwd Raman due to the change in the signal power profile versus fiber length, but there is still a significant net benefit. Multi-wavelength Raman with pump wavelengths separated enough to induce significant pump-to-pump Raman power transfer (multiple order Raman) increases the distance into the fiber over which amplification occurs and improves the OSNR. One penalty in Fwd Raman systems with dual-polarized signals is due to a cross-polarization scattering effect induced by the Raman pumps [6]. It has been shown that second-order Raman pumping (pumps in the 1400 to 1500-nm range) provides the best performance overall, balancing OSNR increases versus penalties [7].

The limitation in Bkwd Raman amplification is mainly due to MPI. In this case higher order Raman pumping in large A_{eff} fiber provides some benefits [8]. The maximum pump power in a commercial system based on efficient 14xx laser diodes is about 2.5 W [4]. Raman fiber lasers have been used to produce more power (7.7 W in [8]) and higher order Raman transfer at the expense of overall system efficiency and complexity.

5. ROPA TECHNOLOGY

Inserting a ROPA into the line fiber which is pumped by residual pump power from Raman amplification results in a significant improvement in OSNR [1], [2]. The ROPA design, location, and pumping method are the factors to improving the performance of UR links. The ROPA is typically located near the receive terminal (Rx ROPA), but may additionally be located near the transmit terminal (Tx ROPA).

The standard Rx ROPA design is just an isolator followed by the Erbium-doped fiber (EDF) whereby the signals enter the ROPA on the isolator side and the EDF is backward-pumped by residual Raman pump power. This simple design suffers from gain saturation effects caused by back-scattered signals and backward propagating ASE from the Raman. The Rx ROPA design can be improved by inserting an isolator in the middle of the EDF and allowing the pump to bypass the isolator. In some cases, routing the pump power to forward-pump the ROPA is beneficial. Typical values of pump power at the Rx ROPA is about 8 mW which can provide for a gain of about 20 dB within the C-band.

A Tx ROPA is not commonly used because it has very limited gain except in specific circumstances. The reason is that the signal power is high on the Tx side and the ROPA gain is limited by pump power.

Consider 10 signals at 0 dBm/ch entering the ROPA at some distance from the Tx terminal. To get 13 dB of gain from a 1480-nm pump with a quantum efficiency of 95% (1480/1550) and a conversion efficiency of 80% (typical) requires about 260 mW of pump power into the ROPA. However, even not considering pump depletion, at a location of 80 km from the Tx terminal and assuming 0.20 dB/km attenuation at 1480 nm, the pump power required at the terminal would be over 40 dBm. With only one signal, the value would be on the order of 30 dBm or 1000 mW which is achievable. Thus a Tx ROPA is only useful in UR links with very limited channel count.

In the case of using both a Tx and Rx ROPA, it is advantageous from a deployment perspective to co-locate both ROPAs in the same undersea housing which requires the distance from both the Tx and Rx terminals to be the same [9].

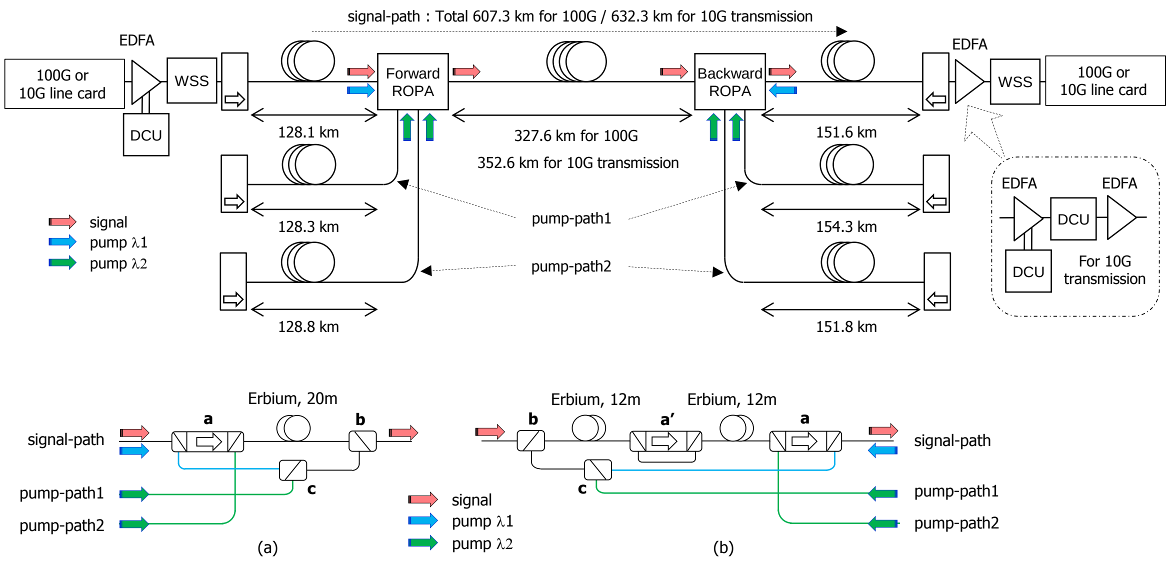
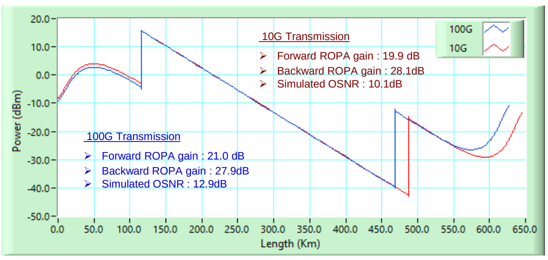


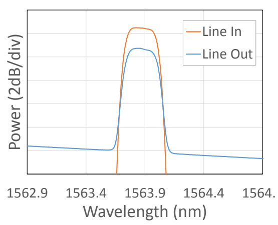
Fig. 1: (TOP) Experimental setup for single 100G/10G channel unrepeatered transmission using two additional ROPA pumping fibers. Insert (dashed box) shows the equipment used for 10G transmission. (BOTTOM) Configurations of (a) forward ROPA, (b) backward ROPA.
a, a' : hybrid filter (consists of sig/pump Mux, isolator, and sig/pump Mux),
b : sig/pump Mux, c : pump λ1/λ2 Mux.

However, better performance is typically achieved by optimizing the distance from each terminal independently.

The distance from the terminal or gain of the ROPA can be increased by using multiple fiber pairs to provide additional pump power to the ROPA. A multi-fiber pumping scheme with novel multi-stage ROPA configuration is shown in Fig 1. The details about this experiment are described in reference [4]. With multiple ROPA pumping paths, the pump wavelengths arriving at the ROPA may need to be different such that they can be multiplexed together (two different colored arrows for pumps in Fig 1). The power profiles in the line fiber are shown in Fig 2 along with single channel spectrum. Note that the Fwd Raman power profile is at a much lower power than the Tx ROPA output power which minimizes the nonlinear penalties. Also note that the combined Raman + ROPA gain in the fiber is about 100 dB and completely compensates for the full span attenuation!



(a)



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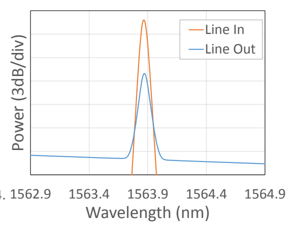

(c)

Figure 2. (a) Simulated signal power distribution, Output OSA spectra of (b) 100G, (c) 10G transmission.

6. FUTURE IMPROVEMENTS

The importance of Raman/ROPA and the limitations of Raman pumping along the signal fiber have been discussed in the preceding sections. These limitations are mostly removed in the additional ROPA-pumping fibers such that high power fiber lasers can be used specifically for both Rx and Tx ROPA pumping. The Erbium-doped fiber in the ROPA helps act as a pumping buffer such that it reduces much of the noise associated with high power pumping. Thus, the penalties due to noise transfer, cross-polarization scattering, and MPI are greatly reduced through the ROPA pumping process. Deploying large A_{eff} fiber allows more ROPA pump power to be utilized at lower Raman gain without increasing the transmission penalties that are proportional to Raman gain. The ROPAs will be placed further into the span fiber to improve the OSNR allowing either greater data capacity and/or longer distances to be achieved. In addition, DSP nonlinear compensation for intra-channel penalties will allow a higher optimum power in the line improving the receive OSNR.

In correlation with repeatered submarine and terrestrial ultra-long haul networks, the future improvements are becoming smaller and more difficult to achieve compared to the progress of the past decade. But, the methods outlined above will allow another step in the path of improved unrepeatered performance.

7. REFERENCES

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