Advanced Technologies for Unrepeatered Transmission Systems and Their Applications

Do-il Chang, Wayne Pelouch, Sergey Burtsev, Bertrand Clesca, Philippe Perrier, Herve Fevrier.
Xtera Communications, Inc. 500 W. Bethany Drive, Suite 100, Allen, TX 75013, USA
Email: dchang@xtera.com

Abstract: This paper reviews the key basic technologies, with a specific focus on distributed Raman amplification, required for long-reach, high-capacity unrepeatered optical transmission systems. We also report several experimental demonstrations with record capacity and reach combinations.
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1. Introduction

Unrepeatered transmission systems are a cost-effective solution to transmit high capacity communication channels over moderate distances of several hundred kilometers without any in-line active elements such as powered amplifiers. The main goal of unrepeatered systems has always been to achieve the longest reach [1-4]; however, increasing traffic demands now require both longer reach and higher transport capacity [5,6]. This paper discusses the key technologies which enable long-reach, high-capacity unrepeatered optical transmission, such as distributed Raman amplification, Remote Optically Pumped Amplifiers (ROPA) and coherent transmission with advanced modulation format and high FEC coding gain. We also reports recent demonstrations that show how these technologies have been combined to maximize the distance and/or capacity in submarine / terrestrial transmission systems.

2. Key Technologies

Distributed Raman amplification (with optical pump sources located at the terminal(s)) is especially important in unrepeatered systems, since it provides gain in the line fiber itself and improves the Noise Figure (NF) of the span. Raman amplification can be applied at the transmitter end (co-propagation with the signal) or at the receiver end (counter-propagation). In this paper, commercially available distributed Raman pump module (Nu-Wave Optima™ SE24) which consists of five pump wavelengths distributed in the range between 1420 and 1500 nm is used. The pump lasers are polarization-balanced for low polarization dependent gain and wavelength multiplexed into the line fiber using a standard high power connector (Diamond E2000PS). The typical Relative Intensity Noise (RIN) of the pump laser diodes is -105 dB/Hz. The module can be used in both the forward and backward directions and provides total pump power up to 1.8 W. When the system requires more power (e.g., large A_{eff} fiber, large number of channels, or spans with high lumped losses), an additional 0.9 W of pump power with two wavelengths between 1400 and 1420 nm can be added by connecting a high power extension module. Multiple pump wavelengths can be configured to allow flexible gain profiles depending on the application. For example, the same Raman pump modules have been used for low [3] and high [6] capacity unrepeatered demonstrations as well as for other applications [7, 8].

Further increase in reach can be obtained with a Remote Optical Pre-Amplifier (ROPA), which consists of a piece of erbium doped fiber placed at about 100 to 140 km from the receiver end. The pump is located in the receiver terminal and conveyed to the ROPA over the line fiber. Before reaching the remote amplifier, the pump also amplifies the signal along the line fiber through distributed Raman amplification. The configuration of ROPA can be modified to provide better performance based on the applications and operators' requirements. Figure 1 shows the example of enhanced ROPA configuration which can provide ultimate performance for low-capacity unrepeatered system.

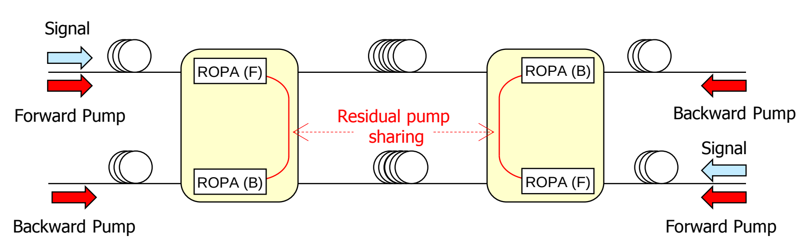

Fig. 1 Enhanced ROPA configuration for Bi-directional Transmission System

Following the trend in terrestrial transmission systems, the demand for unrepeatered systems has quickly moved from 10G or 40G data rates to 100G. In this paper, 100G signal is based on the conventional coherent PM-QPSK format and is modulated at 120 Gbit/s gross rate which accounts for the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC). SD-FEC can correct a Bit Error Ratio (BER) of 1.9 $x10^{-2}$ to less than 10^{-15}. The received signals are real-time processed by Digital Signal Processing (DSP) embedded in the coherent Application-Specific Integrated Circuit (ASIC).

3. Experimental Demonstrations of Unrepeatered Transmission

Figure 2 illustrates the recent demonstration of the longest 100G unrepeatered transmission distance to date as well as a new record for multi-channel 100G unrepeatered transmission [4]. An enhanced ROPA architecture (shown in figure 1), real-time processed 100G coherent transceivers, a commercial Raman system, and 557 km of cabled large effective area ultra-low loss fiber in uncontrolled outside plant (OSP) environment were used for the single channel transmission (523 km for the four-channel transmission). This trial demonstrated the feasibility of extended unrepeatered distances for both terrestrial and submarine applications. The experimental setup which provides the highest capacity [6] is shown in Fig.3. A record capacity of 15 Tbit/s (net capacity of 150 x 100 Gbit/s) unrepeatered transmission over 333.6 km (55.4 dB) and 389.6 km with ROPA (64.3dB) was achieved by using G.652 fiber with a standard C-band ROPA, commercial Raman pump modules and real-time processed 100G channel cards. The results provide a practical solution to increase the capacity of existing unrepeatered spans or the deployment of new systems with ultra-high capacity.

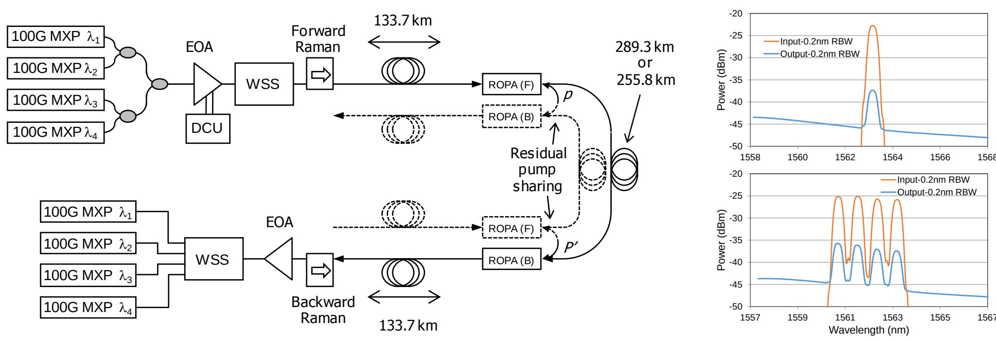

Fig. 2. 120 Gbit/s unrepeatered transmission over 557 km (90.2dB) and 4 x 120 Gbit/s over 523 km

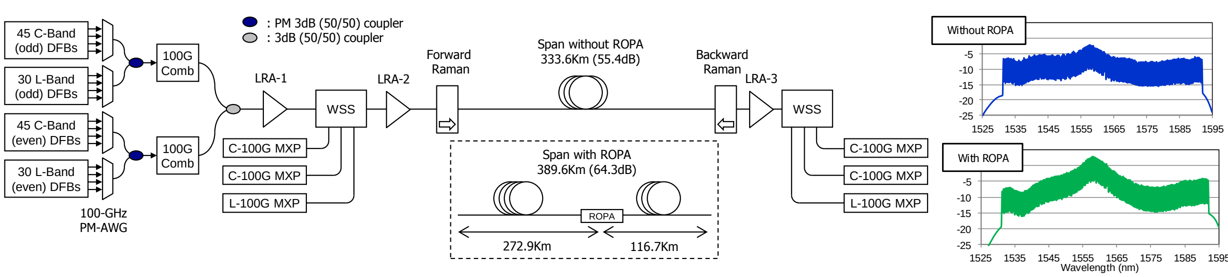

Fig.3. High capacity of 15 Tbit/s unrepeatered transmission

4. Applications in Submarine / Terrestrial systems

The technologies used in unrepeatered systems can also be applied to submarine or terrestrial "repeatered" systems. One such application is subsea links to connect main lands via intermediate islands without signal regenerations or submerged repeaters and associated power feed equipment – yields a more cost effective and thus viable solution. Another supplication is terrestrial route which has remote and hostile areas (security issues, tropical forest, desert…) for which the use of technologies of unrepeatered transmission alleviates the need for intermediate amplification sites (and associated capital and operational expenses). Fig. 4 shows the demonstration of 8 x 120 Gbit/s transmission over a cascade of two very long spans consisting of legacy SMF 303.5 km (59.7 dB) and Pure Silica Core Fiber (PSCF) 342.9 km (60.8 dB) with an intermediate in-line amplifier (ILA). This configuration reduces CapEx and OpEx significantly by removing the need for installation of expensive transponders for signal regenerations at the intermediate site. Another example is provided by the Fig. 5 where an all-optical path exceeding

1,300 km is made of spans of different lengths and attenuations, one of them being 250-km long with a 60-dB optical attenuation. Without unrepeatered system technologies, the channels would have to be terminated at either end of this 250-km, 60-dB span, and imposing costly regeneration sites. The distributed Raman pump modules depicted in the Figure are implemented are highly modular and allow the customization of the amplifier configuration (forward and/or backward Raman pumping) in order to efficiently cope with actual spans attenuations encountered along an all-optical path, while keeping the cost of Raman pump modules under control.

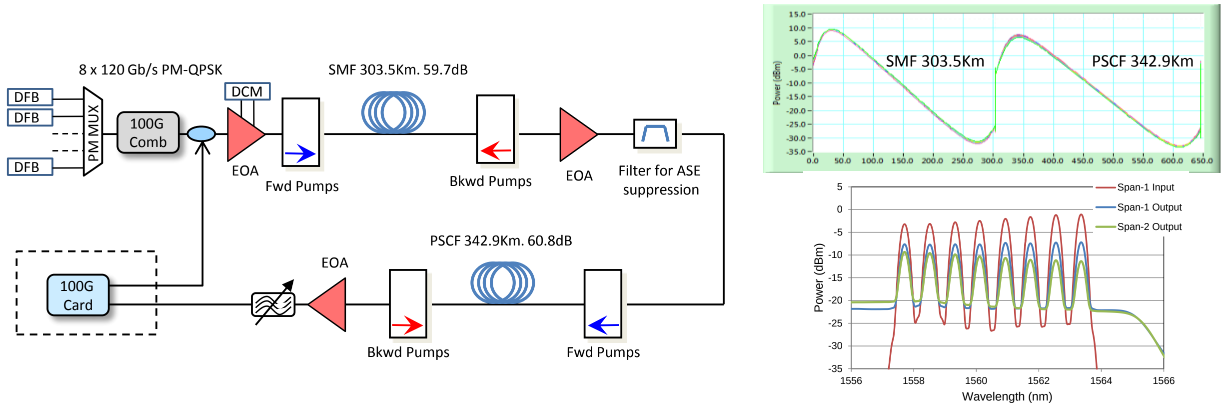

Fig. 4. 8 x 120 Gbit/s transmission over a cascade of two spans with a total loss in excess of 120 dB

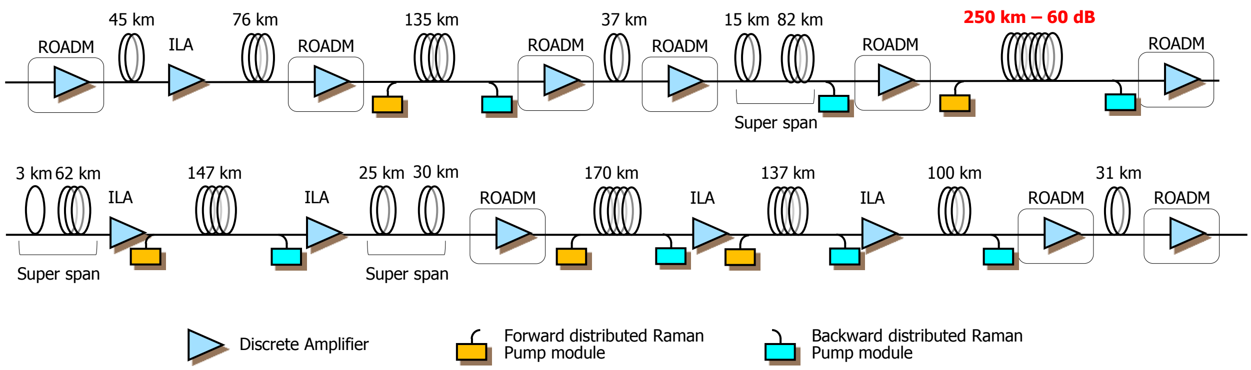

Fig. 5. Example of all-optical path exceeding 1,300 km including one 250-km, 60-dB span enabled by distributed Raman amplification.

5. Conclusions

During the past few years, unrepeatered transmission systems have experienced a rapid evolution to support increased capacity using high order modulation formats. A distributed Raman amplification, ROPA and advanced FEC with coherent detection are key technical enablers to support similar distance with 100G channels as with 10G or 40G data rates. These technologies are not bounded to unrepeatered systems, and can be used in submarine or terrestrial "repeatered" systems to provide significant performance improvements.

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