# ALL-RAMAN TECHNOLOGY ROADMAP FOR HIGH-PERFORMANCE UNREPEATERED DWDM SYSTEMS

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**Abstract:** The transmission of multiple 10 Gb/s signals over a 500 km optical submarine network once required the use of submerged repeaters. Technological advancements, however, now make it possible to span what were once considered repeatered distances with new high-performance unrepeatered DWDM systems. This is accomplished by coupling technologies like Raman amplification with "in-line" technologies like ultra-low loss fibers, remote optically pumped amplifiers and new modulation techniques to obtain significant performance gains for capacity, distance and the transmission of emerging high bit rate channels (OC-768/40 Gb/s). This paper will discuss recent demonstrations that show how these technologies have been combined to maximize capacity over long distances.

## 1 INTRODUCTION

A commercially available all-Raman DWDM system using tightly integrated distributed and discrete amplification is used to set new benchmarks for the capacity and transmission distance of unrepeatered links. Additional gains are investigated using the latest ultra-low loss fibers and an "active line", which could include various components such as isolators, ,and remotely pumped optical amplifiers used in different combinations. Various modulation techniques and forward error correction algorithms are employed to optimize the performance for distance, capacity, and transmission of high-bit rate (OC-768/40 Gb/s) channels or large numbers of 10 Gb/s channels.

## 2 SYSTEM SET-UP

The system functional diagram, shown in Figure 1, depicts two terminal ends of Raman amplification interconnected with 507 km of pure silica core fiber (PSCF) for a total span loss of 91dB (including splice/connector losses between fiber sections). The two terminal ends, representing post and pre-amplification, benefit from the use of lumped Raman amplification (LRA) with the use of dispersion compensating fiber (DCF) as its gain medium. This approach introduces dispersion compensation at both ends of the link to help overcome the accumulated positive dispersion of the line fiber.

While, distributed Raman amplification (DRA) is routinely used as a low noise preamplifier, we seek to maximize its benefits by tightly integrating it with LRA and using it to provide gain at both ends of the span. From past experience, we know that the effectiveness of DRA is quite dependent on both the strategic selection of the pump wavelengths as well as prudent manipulation of the pump power. The proper selection of pump wavelength and power, together with the signal launch power creates a gain profile along the length of the fiber that maximimizes transmission performance. The success of this endeavor is measured by an increase in gain, improved SBS suppression ,and a reduction in non-linear penalties. The forward pump assembly consists of pump laser diodes at different wavelengths multiplexed together and capable of launching power up to 2.5 W in the line fiber. Similarly, a similar pump multiplexing architecture is used in the the backward pump assembly for a maximum launch power of 2.1 W.

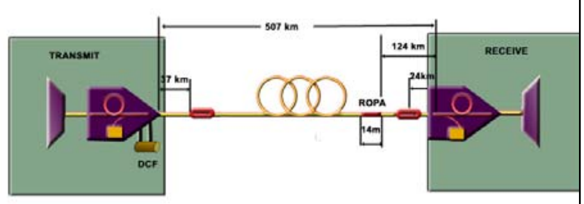


Figure 1: 507 Km Unrepeatered Set-Up

Isolators are introduced in the span to help manage line instabilities (lasing…) resulting from higher pump power in the line .These isolators are strategically placed in the line to allow for a higher gain at the transmit and receive end of the unrepeatered link, improving the over all optical signal-to-noise ratio (OSNR). The optimal placement of isolators in the line was determined by simulation and confirmed by the experiment.

Seeking to further enhance the gain within the line fiber, 14m of commercially available of erbium doped fiber was placed 124km away from the receive end and remotely pumped by the residual Raman pump power . While $Er^{3+}$ ROPA (remote optically pumped amplifier) alone is most effective in the C-band, it is used in this experiment for transmission in the L-band. This sacrifices a little ROPA gain efficiency but allows maximization of Raman gain and provides the best over-all solution. Like the isolators, the optimum position of the ROPA was determined by simulation. The resulting signal power profile is shown in Figure 2. Further transmission improvements were provided using production grade transponders with a NRZ modulation format and a commercially available Enhanced FEC (E-FEC), operating at the standard line rate of 10.709 Gb/s. Because NRZ signals have a strong carrier spectral line that is susceptible to strong Brillouin back-scattering (SBS) in the "forward pumped" Raman amplification region, we introduced a patented SBS suppression method based on a band limited noise broadening of the signal laser diode sources. In terms of transmission penalty and effectiveness, this method turns out to be superior to the commonly used wavelength dithering scheme induced by a tone modulation of the laser diode injection current. The E-FEC is based on an iterative BCH code, operating at a 0.93 code rate. The measured E-FEC performance is given in Figure 3. CHECK

While the counter-propagating pump RIN noise transfer is negligible, the co-propagating pump RIN noise transfer Q penalty is estimated to be no more than 0.1 dB. The measured PDG value of the LRA amplifiers is < 0.5dB, of which the majority, 0.3dB, comes from PDL of the in-line components, and the remainder is due to residual polarization of the pumps. Polarization-mode dispersion of the discrete stage of the LRA amplifiers is <0.6ps, with most of the contribution coming from the LRA gain dispersion compensation fiber.

## 3 EXPERIMENTAL RESULTS

The demonstration was conducted by first transmitting a single 10 Gb/s channel and then adding one 10 Gb/s channel at a time until the transmission was no longer "error-free" after E-FEC.

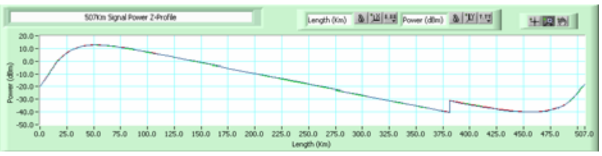

Figure 2: 507 km Signal Power Profile

The measured Q and OSNR dependency on the number of channels, presented in Figure 3. shows that the transmission performance degrades by an approximate rate of 1dB/channel. With E-FEC, a maximum of two channels meet the target Q-value for error-free operation at a BER of $10^{-12}$.

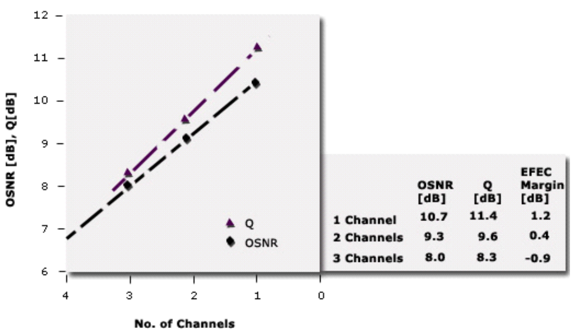


Figure 3: Q, OSNR vs No of Channels

## 4 HIGH-CAPACITY UNREPEATERED SYSTEMS

Unrepeatered submarine networks are undergoing a transition from 2.5 Gb/s to 10 Gb/s. However, due to the recent pressures put on the networks by increasing amounts of video, data and advanced IP services, the addition of higher bit rate services, namely 40 Gb/s (STM-256), is inevitable. Thus, the roadmap for unrepeatered submarine networks must include the ability to transmit these new high-bit rate services over long distances. This demonstration validates the unrepeatered transmission of a mix of 40Gb/s and 10Gb/s signals over a bandwidth of 50nm.

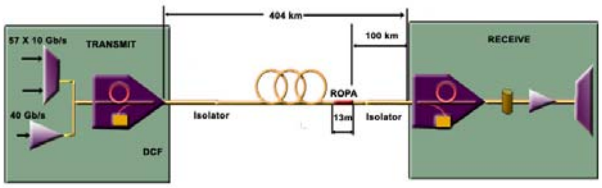


Figure 4: High-Capacity Unrepeatered demonstration set-up

As shown in figure 4, fifty-seven production grade 10 Gb/s NRZ transponders are multiplexed together and combined with a 40Gb/s carrier suppressed return to zero differential phase shift keying (CSRZ-DPSK) transponder. Enhanced forward error correction (E-FEC) is used in both the 40Gb/s and 10Gb/s channels. The ITU compliant channels are located between 1591.68nm and 1546.12 nm, with the 40 Gb/s channel located at 1555.75nm.

The signals are transmitted across 404 km of PSCF with a total loss of 73.9dB at 1550nm using a terminal configuration similar to the one of Figure 1 A remote optically pumped amplifier (EDF) was placed 100 km from the receive end of the link.

To guarantee similar performance of the 10Gb/s and 40Gb/s channels, the OSNR of the 40Gb/s signal should be about 3 dB higher than that of the 10G/s channels. This was achieved by applying pre-emphasis to the 40Gb/s channel with respect to the nominal 10 Gb/s signal launch power.

## 5 HIGH-CAPACITY UNREPEATERED PERFORMANCE RESULTS

The power level of 40 Gb/s signal was set to -5.7dBm while the average launch power of the 10 Gb/s channels was adjusted to -7.7dBm. To obtain an acceptable OSNR (15.4 dB), the 40 Gb/s signal had to be launched at a level that was 2 dB higher than the 10 Gb/s channels. An average of 13.2 dB OSNR was achieved for the 10 Gb/s channels.

Despite launching the 40 Gb/s CSRZ-DPSK modulated signal at a higher power level, the non-linear penalties were small. **Figure 5** provides the optical spectrum of the 40Gb/s channel after 404 km plotted against various launch powers.

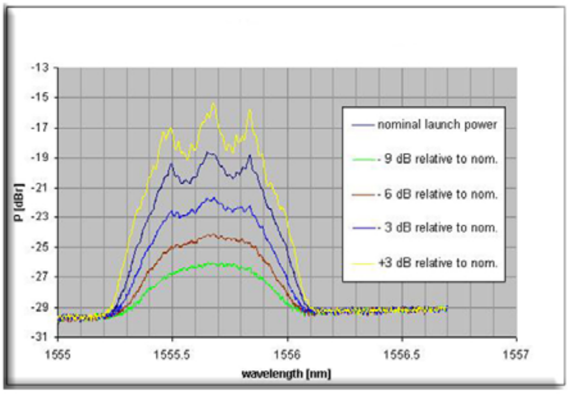


Figure 5:Non-Linear Distortion vs. Launch Power

**Figure 6** shows that the average margin was of 1.8 dB above the E-FEC Q-target for a $10^{-12}$ BER . The Q fluctuated very little during a 12 hour stability test, indicating that the PDG contribution was small.

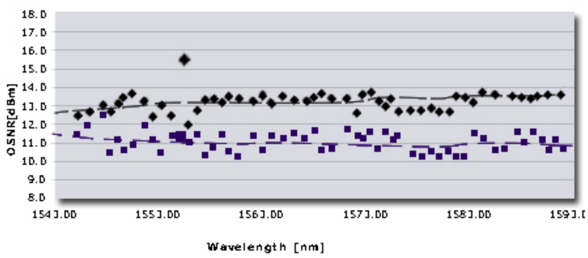


Figure 6:Q ad OSNR [dB] Measurements

The transmit and receive signal spectra are shown in Figure 7. No measurable cross-channel penalty was observed during the test period.

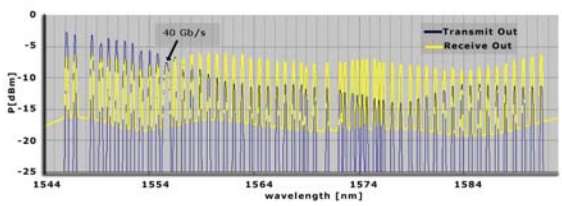


Figure 7:Signal Spectra
(Note that the resolution bandwidth of 0.2 nm makes the 40 Gb/s channel look lower than the 10 Gb/s channels)

This experiment demonstrates the feasibility of 120 channel, transmission over spans 400km long. Doubling of the capacity over such distances could be achieved by migrating to 40 Gb/s channels.

## 6 CONCLUSION

Commercially available all-Raman DWDM provides the foundation necessary to evolve next generation unrepeatered systems to support emerging high-capacity services. The addition of advanced modulation formats, advanced error correction techniques supports the introduction of high-bit rate signals, i.e., 40 Gb/s, to long unrepeatered submarine links. Even longer distances are possible with the recently introduced low-loss PSCF. We have also shown that a ROPA enhanced all-Raman DWDM system provides significant gains for the unrepeatered transmission of a large number of high rate WDM channels. Capacities of 2.4 Tb/s over 400+ km are within reach.


## 7 ACKNOWLEDGMENTS

The authors are thankful to Mintera Corporation for providing the 40Gb/s transponder and for their support of the experiment.