Modeling and experiments of Raman assisted ultra long-haul terrestrial transmission over 7500 km

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Abstract: We have developed a simulator that accurately predicts OSNR and Q of Raman assisted transmission systems. It was validated in a 16×12.3 Gbit/s recirculation loop transmission experiment over 7500 km utilizing 90 km spans. We demonstrated Q values with an average margin of 5.7 dB over FEC limit with 23% overhead.

Introduction

Ultra long–haul transmission distances of 2000-7000 km without regeneration are required to make data centric networks cost effective. These distances are routinely acheived in submarine transmission systems where span lengths typically are about two times shorter than in the terrestrial networks (50 km vs 100 km). Distributed Raman amplification is an enabling technology to achieve long transmission distances by reducing the loss of terrestrial spans. Design of ultra long-haul systems with Raman amplification is extremely challenging since it requires to model transmission very precisely and to account for uncertainties inherently present in terrestrial networks. Furthermore, experimental validation of a design based on straight line testbed is extremely expensive. Therefore, an accurate modeling tool for design of ultra-long haul Raman assisted transmission is indispensable for succesful design.

In this paper we describe a simulator that accurately models Raman assisted transmission. We performed a WDM transmission experiment over 7500 km in a recirculating loop in order to validate the simulator and show good agreement with theoretical results. To the best of our knowledge, the transmitted distance is the longest ever achieved with terrestrial span losses and characteristics.

Simulator

The frame of the present simulator is based on a simulator that models transmission in submarine systems with EDF amplifiers [1,2]. It was validated in many experiments and results are reported elsewhere [1,2]. Raman assisted transmission is simulated based on the model desribed in [3]. It accurately takes into account Raman interaction between pumps, signals, and noise, as well as noise generation and its dependence on the temperature. Computationally effective numerical algorithm was employed to enable fast calculation of Raman gain and noise in terrestrial spans with different length and fiber composition (i.e. different fiber types). Multi-path interference caused by double Rayleigh scattering is also computed and added to the receiver degradations. It is crucial for the accuracy of the model to make a careful experimental determination of the fiber parameters, such as Raman gain shape and fiber loss at the pump wavelengths.

Experiment

The diagram of the recirculating loop is shown in Figure 1. The chain consisted of 5 spans of 90 km E-LEAF fiber and 2 hybrid spans consisting of 42 km of LEAF and DCF fiber. The total length of the loop was 570.7 km. Each span was pumped with Corning® PureGain™ Raman amplifier to obtain 10 dB on-off gain and signal was further amplified with single coil EDF amplfier with 4.5 dB noise figure. Raman and EDF amplifiers were tuned to provide total flat gain in the 1542-1556 nm range with 0.25 dB ripple. The gain ripple accumulated through the loop was cleaned with a gain equalizing filter (GEF). After GEF 9 km of SMF fiber was added to tune the zero dispersion of the loop to 1549 nm.

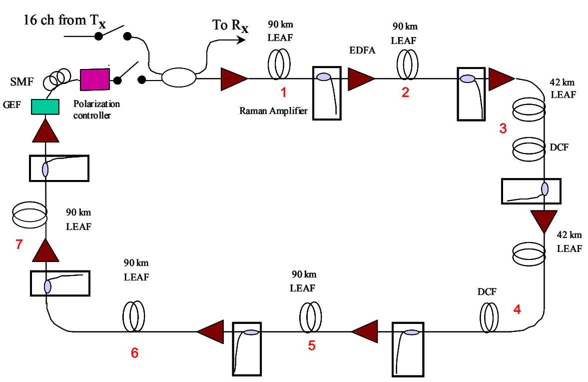

Figure 1. Diagram of experimental set-up.

Transmitter generated 16 WDM channels from 1542.94 nm to 1554.94 nm with 100 GHz channel spacing. The modulation format is chirped return-to-zero (CRZ) at a line rate of 12.3 Gb/s. We chose the GEF to flatten the noise floor after 7500 km propagation. Then, channel power was pre-emphasized to equalize OSNR. The resulting spectrum at 7500 km exhibits a power per channel ripple of 3 dB. At the receiver, the WDM channels are demultiplexed using an optical filter before BER is measured and Q factor calculated. We also measured optical signal to noise ratio (OSNR) as function of distance to validate simulator OSNR prediction.

Results

We modeled the propagation in the recirculation loop by assuming that all spans with E-LEAF fibers were identical with the experimentally measured average fiber parameters. The two hybrid spans are also assumed identical with the DCF parameters corresponding to the average parameters of this fiber type. First, we simulated the amplifier chain, i.e. a single round trip in the loop. The measured and simulated OSNRs are shown in Figure 2. The maximum difference between them is 0.3 dB. The OSNR exhibit ripple of 1.5 dB due to combination of the higher attenuation at blue Raman wavelength and non-flat Raman gain.

After we obtained good agreement for the chain we measured and computed average OSNR as a function of number of recirculations in the loop. The comparison is shown in Figure 3(a). The simulated OSNR deviated from the measured by 0.03 dB at 7500 km. The simulator also shows good agreement between measured and simulated OSNR as a function of wavelength (see Figure 3(b)). The maximum difference is 0.53 dB and can be attributed to the PDL in the recirculation loop. We note that the OSNR at 7500 km is fairly flat due to OSNR pre-emphasis at the transmitter.

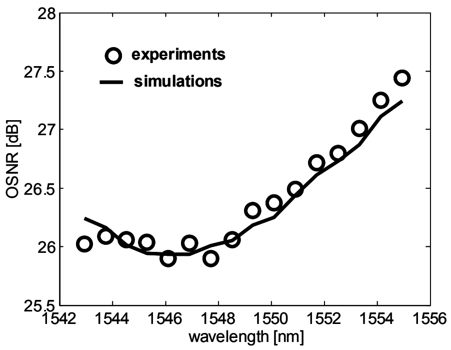

Figure 2. Simulated and measured OSNR as a function of wavelength for amplifier chain.

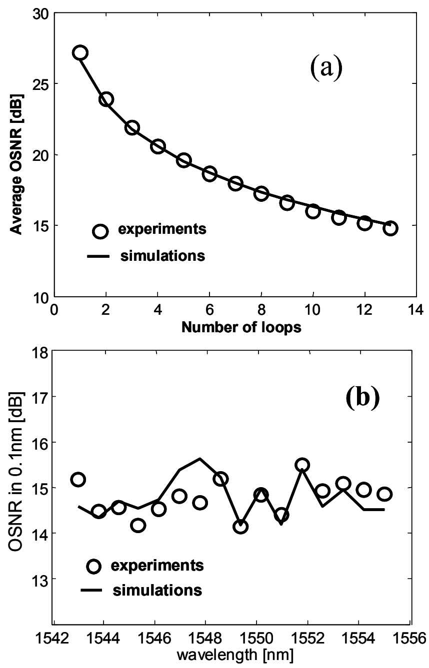

Figure 3: (a) Simulated and measured average OSNR as a function of roundtrips in the loop. (b) Simulated and measured OSNR as a function of wavelength after 13 loops (7500 km).

We computed Q-values for the cases of –3 dBm and –1 dBm power per channel launched into the fiber. The comparison between measured and computed Q are depicted in Figure 4(a) and (b). The maximum deviation after 7500 km is 1.3 dB, which we attribute to PDL. In the case of –3 dBm per channel all channels have the same performance, while with –1 dBm per channel the center channels are degraded due to SPM. The nonlinear penalties occur at the center channels where accumulated dispersion is very low. For these channels RZ pulses periodically re-compress causing accumulation of nonlinear impairments. We checked with experiments and simulations that the nonlinear penalties are single channel effects.

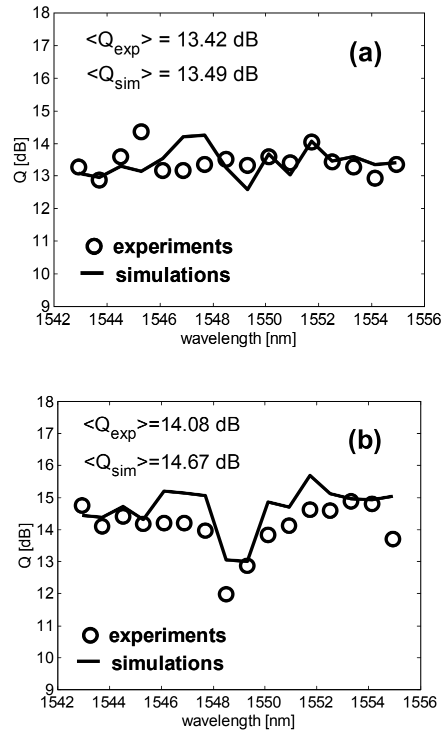

Figure 4: Measured (circles) and simulated (solid lines) values of Q after 7500 km. Power per channel (a) -3dBm (b) –1dBm.

The strong nonlinear penalty around zero average dispersion is likely suppressed in terrestrial fiber routes due to variability of span lengths and dispersions. Indeed, simulations show that it is not present in systems with varying fiber spans and dispersions as in actual existing fiber routes.

Note that with 23% FEC overhead, Q = 8.3 dB corresponds to error-free transmission. With –1 dBm per channel average Q is 14 dB, thus providing an average system margin of 5.7 dB to the FEC limit. Minimum margin in the recirculation loop is 3.7 dB likely to be larger in a real system with span length and dispersion variability.

Conclusion

We have developed a simulator that accurately predicts OSNR and Q of Raman assisted transmission systems. It was validated in a recirculation loop transmission experiment over 7500 km. We demonstrated Qs with average margin of 5.7 dB over FEC limit with 23% overhead.

References

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