Capacity optimization strategies in an unrepeatered system

H. Bissessur, A. Busson, D. Kravchenko, F. Hedaraly
Alcatel Submarine Networks, 91940 Les Ulis, France
Author e-mail address: hans.bissessur@asn.com

Abstract We show 11% capacity improvement in an unrepeatered link at a constant baud-rate, by adjusting the bit-rate of a real-time transponder on a channel-per-channel basis, compared to a fixed bit-rate transponder.

1. Introduction

Submarine unrepeatered links operate without in-line amplifiers, and bridge hundreds of kilometers thanks to the low attenuation of modern optical fiber and the help of Raman amplification. Like their repeated counterparts, unrepeatered systems are challenged to transport the highest capacity over the longest distance; therefore, a compromise is found from an ultra-long distance with only a few channels to ultra-high capacity over moderate distances. In modern systems, transponder flexibility is applied whenever there is some excess margin with one given format in order to reach the optimum configuration with no excess margin, all channels then carrying the same format and bit-rate. The bit-rate can be adapted by changing the FEC overhead or the modulation format.

In previous high-capacity unrepeatered demonstrations, two types of experiments have been presented: either with a fixed bit-rate (usually with real-time transponders) [1-3] or with bit-rate adjustable transponders (usually with off-line equipment) [4-6]. In the latter case, the bit-rate is adjusted channel by channel (or calculated from each channel's GOSNR). The capacity claims may be different in both cases. A detailed comparison, based on the GSNR, in a wideband S+C+L multispan repeated system has shown an improvement of 5% in achievable throughput [7] between uniform launch power and per-channel optimized launch power. In an unrepeatered system, uniform launch power is not applied due to the large Stimulated Raman Scattering (SRS) between channels (see e.g. [3]), and the starting point is therefore different.

In this paper, we analyze a full C-band-unrepeatered system with different channel launch power conditions, first at a fixed bit-rate applied globally to all the real-time WDM channels, then with an adjustable one. We take a system that is at the limit of a given format at 350 Gb/s/channel and apply channel by channel transponder flexibility (i.e, different bit-rates to different channels) in order to optimize the system's capacity. We change the bit-rate with 50 Gb/s granularity and optimize the total capacity by optimizing both the total launch power and the individual channel power. Based on these experimental results, we estimate the achievable capacity with 1 Gb/s granularity and extrapolate 11% improvement.

2. Experimental System configuration

The set-up of the experiment is shown in Figure 1 and involves three real-time transponders with adjustable bit-rates and modulation formats. We choose to operate at nearly constant baud rates (between 74.3 and 74.5 GBd) with 16-QAM Probabilistic Constellation Shaping (PCS) modulation formats with an entropy ranging from 2.4 to 3.8, for which we obtain bit-rates of 250, 300, 350, 400 and 450 Gb/s. The FEC is the same in all cases. We analyze 59 channels from 1530.02 to 1567.13 nm with 80 GHz spacing covering the whole C-band. The wavelengths of our 3 independent real-time transponders are set to adjacent channels λ_{N-1}, λ_N and λ_{N+1} respectively. The remaining channels are emulated by combining a broadband Amplified Spontaneous Emission (ASE) source and a Wavelength Selective Switch (WSS). ASE shaping is implemented such that the spectral shape of actual data channels is replicated. Then the ASE channels are combined with the transponders by an optical coupler. We apply the same ASE loading to the different formats around 74.4 GBd. The BER & receiver OSNR of the channel at λ_N are measured, then the wavelengths are tuned to the next channels. We thus emulate a real WDM system at 74.4 GBd with 80 GHz channel spacing where the modulation format and the bit-rate can be adjusted on a channel by channel basis.

The 175 km-long link consists of G.654.C Pure Silica Core Fiber (PSCF) having an effective area of 80 μm^2 and an attenuation of 0.175 dB/km at 1550 nm. We try to keep a simple but flexible transmission line, over which the total booster power and channel power can be changed: the high-power booster (30 dBm) is followed by a Variable Optical Attenuator (VOA1) to adjust the total launch power; another VOA (VOA2) is used to control the link loss.

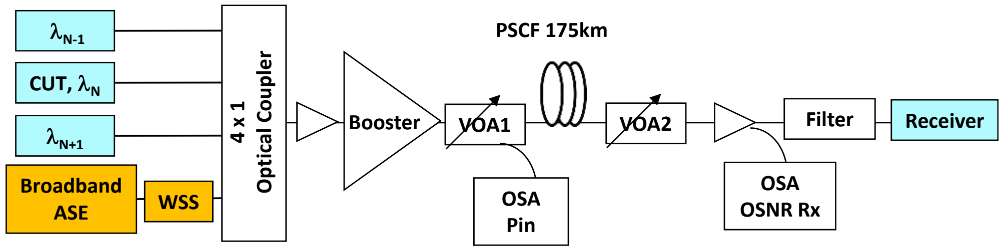

Fig. 1. Experimental set-up with 3 real-time transponders.

3. Transmission results in different scenarios

In a first step, the launched power profile is optimized for the 350 Gb/s transmission. We adjust the link loss (through VOA2) so that we reach Q^2 factors around our target of 6.5 dB; we keep this setting for all the next measurements. The results are shown in Fig.2. After equalizing all the channels in Q^2, we find values between 6.4 and 6.9 dB; the average OSNR at the receiver is 18.5 dB/0.1nm. The line output and the OSNR are tilted to compensate for Non-Linear (NL) penalty. The first channels with Q^2 around 6.6 dB cannot be improved because they reach their optimum NL power. In these conditions with a fixed bit-rate, the total capacity reaches 20.65 Tb/s. This is the maximum achievable throughput as long as we require all the channels to operate at the same bit-rate. The equalization results in a high tilt in launch power (more than 8 dB), because of energy transfer from the lower wavelength channels to the higher wavelength channels by SRS.

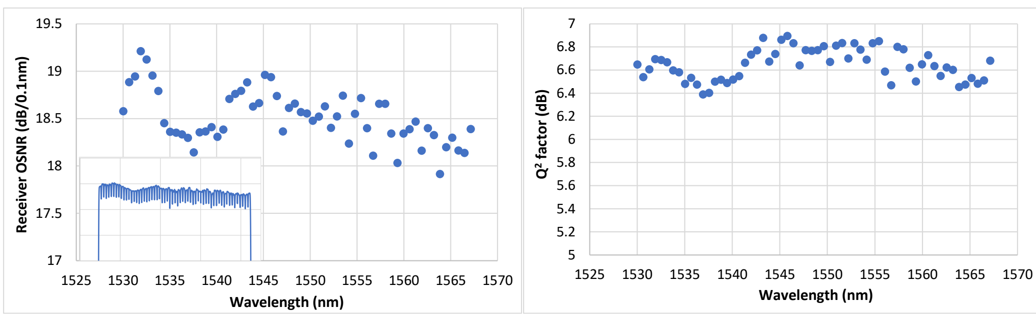

Fig. 2. Receiver OSNR (left) and Q^2 factors (right) of the 59 channels when they are all modulated at 350Gb/s. The insert in the left Figure shows the spectrum at the output of the line (5dB/graduation).

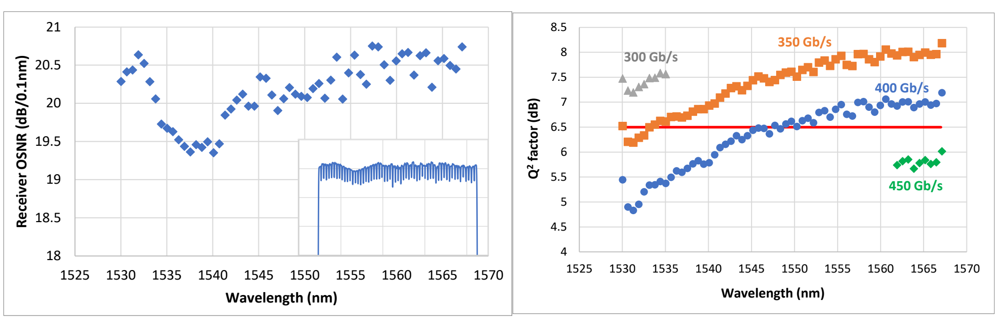

Fig. 3. (a) Receiver OSNR of the 59 channels at the receiver end. (b) Q^2 factor results of 59 channels with different modulation formats (300, 350, 400 and 450 Gb/s). The Q factor target considered for the capacity estimation is shown in a red line.

Starting from this scenario, we first increase the launch power by 1.8 dB. Obviously, since the low-wavelength channels are already at their non-linear limit, they will be degraded and will not support the 350 Gb/s bit-rate anymore. We should however improve the high-wavelength channels. The Non-Linear heuristic described in [7] is not straightforward to apply in an experiment and we actually optimize the power tilt at the transmitter. We then measure all the channels at 300, 350, 400 and 450 Gb/s. Fig. 3 shows the OSNR and Q^2 results. The average OSNR has been increased to 20.2 dB/0.1nm. As expected, the performance of the channels at the lower wavelength end has decreased and these channels have to operate at 300 Gb/s. On the other hand, all the channels above 1545 nm (except one) can be operated at 400 Gb/s. Operation at 450 Gb/s is not possible with the criterion of Q^2=6.5 dB that we apply here. By applying 300 Gb/s at low wavelengths, 400 Gb/s at high wavelengths and 350 Gb/s in the middle of the spectrum, we can reach a total capacity of 22.15 Tb/s, which corresponds to an improvement of 7% vs the transponder at a fixed bit-rate.

We finally increase the total power by a further 1.0 dB (i.e., 2.8 dB more than the power with the transponders at a fixed bit-rate in the configuration of Fig. 2), which gives a strong OSNR tilt (average OSNR = 21.1 dB/0.1nm). This power should be close to the optimum as calculated by our simulation tool. We repeat the measurement of all the channels (see Fig.4). This time, a few channels work at 450 Gb/s, while the bit rate is reduced for others. The total capacity is now 22.35 Tb/s, an improvement of 8% vs the transponder at a fixed bit-rate, but only a small improvement vs the previous case. Further improvement could be obtained by bringing all the low bit-rate channels to their operating limit (by reducing their power) in order to improve the high-wavelength channels.

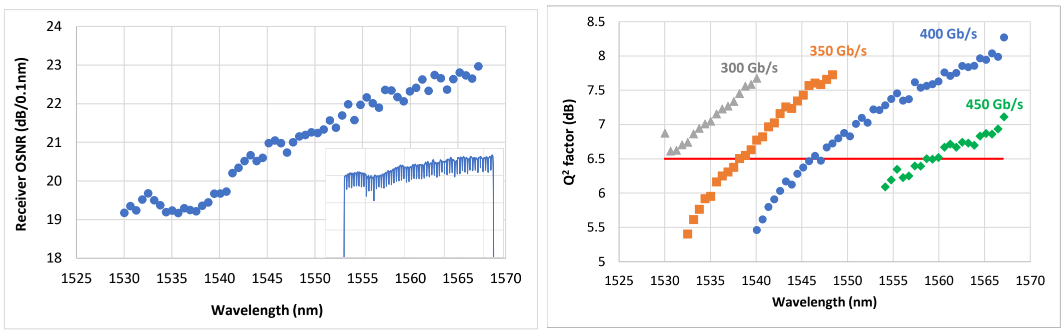

Fig. 4. Results after 2.8 dB increase in launch power : (a) OSNR of the 59 channels at the receiver end. (b) Q^2 factor results of 59 channels with different modulation formats (300, 350, 400 and 450 Gb/s).

The present experiments are carried out with a transponder with a granularity of 50 Gb/s between formats. Some unrepeatered experiments are made with a much smaller granularity (FEC code granularity of 0.01). If we want to extend our results to a granularity of 1 Gb/s and get a finer picture of our experiments, which would then compare with the GSNR experiments with a small granularity, we can rework the measurement results and extrapolate the exact bit-rate of each channel. Table 1 summarizes our different results: for the same unrepeatered link, allowing channel by channel transponder flexibility with 1 Gb/s granularity increases the capacity from 20.73 Tb/s to 22.98 Tb/s, i.e., an improvement of 11%.

Table 1. Capacity achievements under different conditions

Conditions	Δ Launch Power	Capacity (Tb/s), 50 Gb/s granularity (measurement)	Capacity (Tb/s), 1 Gb/s granularity (estimation)
Equalized (350 Gb/s)	0 (Ref)	20.65	20.73
Unequalized 1	+1.8	22.15	22.80
Unequalized 2	+2.8	22.35	22.98

4. Conclusion

We report experiments over a fixed unrepeatered line under different operating conditions. Over a link that is at the limit of fixed bit-rate 350 Gb/s transmission with 59 equalized channels, we can increase the capacity by 8% by taking advantage of transponder flexibility and optimizing the channel bit-rate with 50 Gb/s granularity. We extrapolate an improvement of 11% with a granularity of 1 Gb/s as sometimes used in unrepeatered experiments.

5. References

[1] H. Bissessur et al, "Real-Time Unrepeatered C-Band Transmission of 30.5 Tb/s over 276.4 km and 29.45 Tb/s over 292.5km" in OFC, W1I.1 (2021).
[2] B. Zhu et al, "25.6 Tbit/s (64x400Gb/s) Real-time Unrepeatered Transmission over 320 km SCUBA Fibers by 400ZR+ Pluggable Modules" in ECOC, We3c1.4 (2021).
[3] J. Li et al, "16 Tb/s Real-time Unrepeated Transmission over 420 km G.654E fiber," in ECOC (2020).
[4] H. Bissessur et al, "Unrepeatered transmission of 29.2 Tb/s over 295 km with Probabilistically Shaped 64 QAM" in ECOC, Th1G.4 (2018).
[5] A. Busson et al, "Unrepeatered C-Band Transmission of 35.5 Tb/s Capacity over 291 km using 128 GBd DP-16-QAM" in OFC, Tu2.G.4 (2023).
[6] S. Almonacil et al, "C-band Unrepeated Transmission System over 291-km at Net Throughput of 41.3-Tbps without ROPA" in ECOC, Th2.B.4 (2023).
[7] S. Landero et al, «Modeling and Optimization of Experimental S+C+L WDM Coherent Transmission System,», Th3F.4 (OFC2023).