HOW COHERENT UNREPEATERED SYSTEMS CAN BE OPTIMISED FOR HIGH-CAPACITY

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Abstract: Based on different high-capacity experiments, we analyse the trade-off between the use of 40 Gb/s and 100 Gb/s bit rates, the increase of channel count and the reduction of channel spacing to increase the capacity of long reach unrepeatered links. We show that the 100 Gb/s bit rate with 40 GHz channel spacing provides the higher capacity. We demonstrate 6 Tb/s capacity transmission over 437 km and validate the configuration for 10 Tb/s. We then show that, for 5 Tb/s capacity, the reach can be improved using dual carrier BPSK at 100 Gb/s.

1. INTRODUCTION

Unrepeatered transmission systems aim at spanning long distances without any in-line active elements, thus reducing the line complexity and the overall system cost. They are used to link islands or concatenated with repeatered submarine systems. Their reach is obtained thanks to powerful booster and laser pumps located at both ends of the system to overcome the large link loss. The longest reach, 601 km, is obtained at 10 Gb/s [1], but at this bit rate the maximum achievable capacity is only 1.5 Tb/s.

This paper describes how the up-to-date technologies allow to further increase this capacity. We present different configurations that can be applied. Then, based on several unrepeatered experiments, we discuss the trade-offs between these and conclude as for the optimum configuration.

2. PARAMETERS IMPACTING CAPACITY

The straightforward means to increase the capacity of a transmission system are to increase the channel bit rate and/or the channel count.

Table 1 sums up the main parameters and the performance published for various long reach (> 350 km) unrepeatered systems with capacity in excess of 2 Tb/s.

Ref	Channel count x bit rate	Channel spacing (GHz)	Link length (km)	Link loss (dB)	Fibre effective area (µm²)	FEC type
[2]	26x100G (2.6Tb/s)	50	401	66.9	115	HD
[3]	40x100G (4.0Tb/s)	50	365	59.5	128	HD
[4]	64x40G (2.56Tb/s)	50	440	71.5	115	HD
[5]	64x40G (2.56Tb/s)	33	468	76.1	135	HD
[6]	34x100G (3.4Tb/s)	mix 50/100	433	74.4	75	SD
[7]	60x100G (6.0Tb/s)	40	437	71.0	135	SD

Table 1: Main parameters and performance of published high capacity unrepeatered experiments

Among the numerous modulation formats studied at 40 Gb/s and 100 Gb/s, those based on Polarization Division

Multiplexing (PDM) and Phase Shift Keying (PSK), such as Binary PSK (BPSK) and Quaternary PSK (QPSK) are the preferred choice because of their compatibility with the usual 50 GHz channel spacing. These newly developed modulation formats associated with coherent detection are now available for commercial deployment at 40 Gb/s and 100 Gb/s.

Obviously, increasing the bit rate from 40 to 100 Gb/s allows a higher total capacity. However, the OSNR requirement is higher (by typically 3-4 dB) and the optimum operating channel power is lower for 100 Gb/s PDM-QPSK than 40 Gb/s PDM-BPSK. The 100 Gb/s line rate can also be realised with dual carrier 50 Gb/s PDM-BPSK: in this case OSNR requirement and Non Linear Threshold (NLT) are comparable to those of the 40 Gb/s PDM-BPSK format.

The other way to implement high capacity is to increase the channel count. In this case, the occupied optical bandwidth increases and some channels are located in the low wavelength range where fibre attenuation and Raman Noise Figure (NF) are high (Figure 1). Thus, those channels have degraded performance. For example, optical bandwidth needed to transmit 2.6 Tb/s capacity is shown in Figure 1: either with 26 channels at 100 Gb/s or with 64 channels at 40 Gb/s (both with 50 GHz spacing). For 64 channels, the worst NF is 0.8dB higher and 1dB more link loss is experienced (for 400 km long link) by channels located in the low wavelength range compared to the 26 channels case.

To overcome this limitation, channel spacing can be reduced to gather the channels in the region of the optical spectrum where the link characteristics are better. Closely spaced channels require tight filtering at the output of the link before detection.

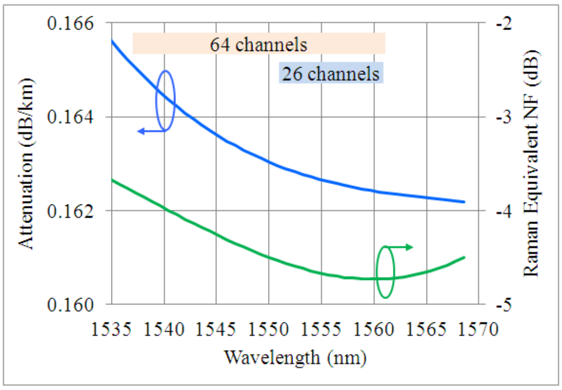

Figure 1: Evolution of fiber attenuation and Raman NF versus wavelength.

Figure 2 shows the evolution of the Q²-factor versus receiver filter bandwidth for back-to-back measurement of one channel at 40 Gb/s: filtering penalty is moderate down to 33 GHz bandwidth but increases sharply for lower bandwidth. Therefore, a practical 40 Gb/s PDM-BPSK system is limited to 33 GHz spacing today. Similarly, 40 GHz spacing is applicable to 100 Gb/s PDM-QPSK channels.

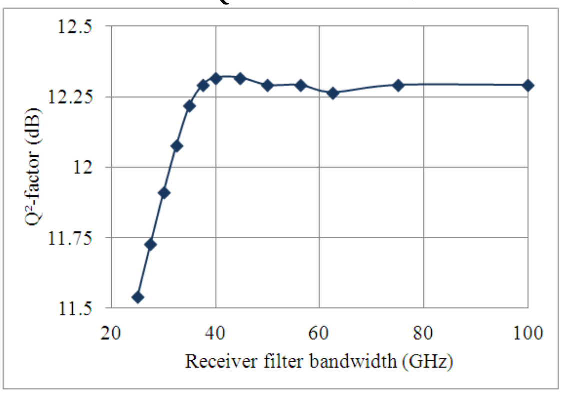

Figure 2: Impact of receiver filter bandwidth on one 40 Gb/s channel

Considering the 32 nm typical amplifier bandwidth, Table 2 gives the maximum capacity achievable with 40 Gb/s PDM-BPSK, 100 Gb/s Dual Carrier (DC) PDM-BPSK and 100 Gb/s PDM-QPSK with realistic channel spacings. It shows that capacity is limited to 4.8 Tb/s with 40 Gb/s bit rate, and improved up to 10 Tb/s thanks to 100 Gb/s bit rate. Capacities above

10 Tb/s can be achieved in the future thanks to higher bit-rates (for example 200 Gb/s in [8]).

Bit rate (Gb/s)	Channel spacing (GHz)	Maximum capacity (Tb/s)
40	50	3.2
40	33	4.8
100 (DC)	100	3.2
100 (DC)	80	5
100	50	8
100	40	10

Table 2: Maximum capacity for different channel spacings and bit rates

3. TOWARD 10 Tb/s CAPACITY

To determine the trade-off between channel spacing and channel count to achieve high capacity, we compare transmission experiments, which all rely on a high-power booster at the transmitter end and a 3rd order Remote Optically Pumped Amplifier (ROPA) at the receiver end.

A schematic of the common experimental set-up is shown in Figure 3**Error! Reference source not found.**. DFB laser sources are combined two by two: odd and even channels are PDM-PSK modulated. Then, they are combined thanks to an interleaver (IL) and amplified by a powerful booster. The line fibre is Enhanced - Pure Silica Core Fiber (E-PSCF) with 115 µm² effective area. The ROPA is a length of Erbium doped fiber counter-directionally pumped by a Raman fiber laser located at the receiver side. This Raman pump delivers up to 7 W at 1276 nm: this energy is transferred to a wavelength band around 1350 nm and then to 1485 nm, through cascaded Raman amplification over the link fiber: one more Raman transfer from 1485 nm to the C-band provides channel amplification in the remote section (from receiver to ROPA). At the receiver end, each channel is selected by a tunable filter and sent to the coherent mixer. Signal processing compensates for signal distortion induced by optical fiber transmission (including chromatic dispersion) and realizes symbol identification.

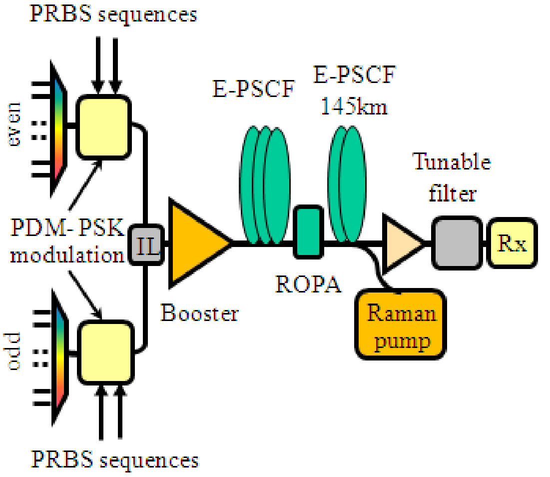

Figure 3: Experimental set-up

We set up two experiments with 100 Gb/s PDM-QPSK channels.

In our first experiment, we use laboratory prototypes to transmit 26 channels, 50 GHz spaced over 401 km [2], thus achieving 2.6 Tb/s capacity. In this case, PRBS sequences feeding the modulators account for Hard Decision-FEC (HD-FEC) and protocol overhead (total = 12%). For 66.9 dB total link loss (fibre attenuation is 0.167dB/km), OSNR and Q^2-factor spectra are fairly flat over the 10.1nm channel bandwidth; their mean values are 17.1dB/0.1nm and 9.1dB, respectively.

In a second experiment, we transmit 60 channels to get 6 Tb/s capacity [7] with technologies providing better performance.

To relax OSNR requirement, Soft-Decision FEC (SD-FEC) is used: it reduces the Q^2-factor limit by more than 2 dB compared to the 8.5 dB limit for HD-FEC at the expense of 20% overhead (7% for HD-FEC).

The fibre is E-PSCF except at both ends where 50 km of E-PSCF are replaced by Ultra Large effective Area PSCF (ULA-PSCF) with an effective area of 135 µm². This high effective area fibre increases the NLT compared to E-PSCF: from their effective area ratio, 0.8 dB improvement is expected.

To take full benefit of low fibre loss and low Raman NF region, 40 GHz channel spacing is chosen. A simple unrepeatered configuration is set up to determine the channel penalty due to the spacing. Two sets of 4 channels are PDM-QPSK modulated at 120 Gb/s (20% overhead is included for SD-FEC): odd and even channels are interleaved and amplified. A variable optical attenuator is used to adjust the channel power injected into the line fibre. At the receiver end, one channel is selected and its Bit Error Rate (BER) is measured. Figure 4 shows that reducing the channel spacing from 50 GHz to 40 GHz induces a Q²-factor penalty of 0.7 dB at optimum channel power. This penalty is moderate compared to the improvement brought by locating the channels in the wavelength range of low fibre loss and low noise figure.

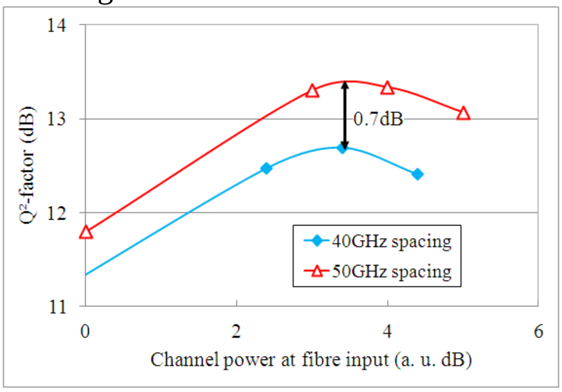

Figure 4: Comparison of 40 and 50 GHz spacings for 100 Gb/s bit rate

Altogether, a 437 km long transmission is realised. For 71.0 dB link loss (fibre attenuation = 0.163 dB/km), mean OSNR and Q²-factor values are 15.3 dB/0.1 nm and 7.8 dB. This 6 Tb/s transmission experiment shows the practicality of the 40 GHz spacing for an unrepeatered system at 100 Gb/s.

Applying this configuration to the 32 nm available bandwidth provides 10 Tb/s capacity. Then, channels located in the low wavelength range suffer from higher Raman noise figure and fibre attenuation. From Figure 1, expected reduction of link budget is around 2dB or 15 km.

These two experiments show that 100 Gb/s PDM-QPSK modulation format is the appropriate choice, either with 50 GHz or 40 GHz channel spacing, to design high capacity unrepeatered links up to 400 km.

4. LONGER REACH WITH BPSK FORMAT

This link budget can be improved, at the expense of total capacity, by relaxing OSNR requirement, which can be achieved with 40 Gb/s bit rate.

To determine the configuration allowing longer reach while keeping high capacity, we set up two experiments at 40 Gb/s bit rate to transmit 64 PDM-BPSK channels (2.56 Tb/s capacity).

In the first case, channels are 50 GHz spaced [4]. In the set-up of Figure 3, BPSK modulators are used and link fibre is E-PSCF with 0.163dB/km attenuation. Measured OSNR and Q²-factor spectra are not flat (Figure 5**Error! Reference source not found.**): their values vary, respectively, from 11.3 dB/0.1nm to 13.0 dB/0.1nm, and from 8.8 dB to 11.2 dB over the 25.2 nm optical bandwidth for a 71.5 dB total link loss (440 km length). The reach is clearly limited by the channels located in the low wavelength range.

To overcome this limitation, a second set-up with 33 GHz channel spacing [5] is implemented. In Figure 3**Error! Reference source not found.**, modulators and receiver are replaced by PDM-BPSK linecards, which include a real-time receiver with all algorithms embedded. The link fibre is E-PSCF except at both ends where 80 km of E-PSCF are replaced by ULA-PSCF. Here, the OSNR and Q²-factor spectra are fairly flat over the 16.9 nm bandwidth. For 76.1 dB total link loss, mean OSNR and Q²-factor values are 10.9 dB/0.1 nm and 9.6 dB.

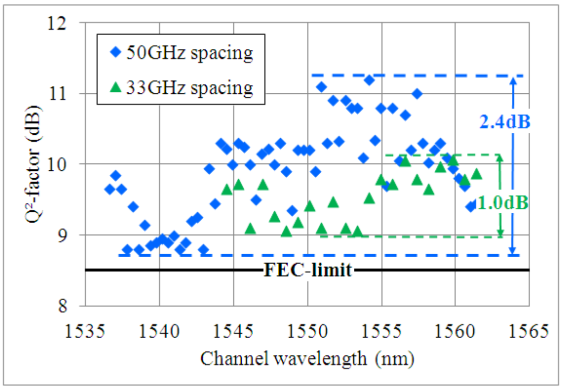

Figure 5: Q²-factor for 64 x 40 Gb/s transmission with 50 GHz and 33 GHz channel spacing

Thus, the reduction of channel spacing from 50 GHz to 33 GHz improves the transmission distance for medium capacity using 40 Gb/s PDM-BPSK format.

This result can be applied to dual carrier PDM-BPSK to provide 100 Gb/s line rate with moderate OSNR requirement and high non linear threshold. Transmission of channels consisting of two carriers at 50 Gb/s with 40 GHz spacing should provide similar performance as only 1 dB degradation is expected from carrier bit rate ratio.

5. CONCLUSION

The 100 Gb/s bit rate is the appropriate choice to realise high-capacity unrepeatered links up to 400 km. Associated to 40 GHz channel spacing, we demonstrate that it is an optimized choice to transmit up to 10 Tb/s capacity.

The use of 100 Gb/s line rate consisting of 50 Gb/s dual carrier BPSK is relevant to provide higher reach (up to 450 km) for 5 Tb/s capacity.

6. REFERENCES

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