

# Transmission of 96×100Gb/s with 23% Super-FEC Overhead over 11,680km, using Optical Spectral Engineering

M. Salsi<sup>1</sup>, C. Koebele<sup>1</sup>, P. Tran<sup>1</sup>, H. Mardoyan<sup>1</sup>, E. Dutisseuil<sup>1</sup>, J. Renaudier<sup>1</sup>, M. Bigot-Astruc<sup>2</sup>, L. Provost<sup>2</sup>, S. Richard<sup>2</sup>, P. Sillard<sup>2</sup>, S. Bigo<sup>1</sup>, and G. Charlet<sup>1</sup>

<sup>1</sup> Alcatel-Lucent, Bell Labs, Route de Villejust, 91620 Nozay, France

<sup>2</sup> Draka Communications, Route de Nozay, 91460 Marcoussis, France

Author e-mail address: massimiliano.salsi@alcatel-lucent.com

**Abstract:** We transmit 96 PDM-QPSK channels at 100Gb/s over 11,680km, matching the best capacity × distance product reported, but with C-band-only EDFAs. 2.7b/s/Hz spectral density is obtained, despite 23% super-FEC overhead, with optical spectral engineering.

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## 1. Introduction to the style guide, formatting of main text, and page layout

Recent publications have shown the possibility of covering transoceanic distances with coherent-based modulation formats at 100Gb/s [1–4]. A large majority of them use Raman amplification to provide a good optical signal-to-noise ratio (OSNR) over the extremely long distances. However, it has not yet been implemented in any commercial submarine cable, where well-mastered, reliable technologies are mandatory.

We use here only erbium-doped fiber amplifiers (EDFAs), similarly to recent works [4,5]. We transmit 96 channels at 100Gb/s with polarization-division multiplexed quadrature phase-shift keying (PDM-QPSK), for a cumulative capacity of 9.6Tb/s, over 11,680km in a recirculating loop based on 50km ultra-large effective area fiber spans. We therefore match the best reported capacity × distance product to date (112Pb/s·km) [3], but without costly L-band or Raman amplification [3] and by relying on standard receiver algorithms, free of complex detection schemes such as maximum a posteriori probability (MAP) estimation [4]. We show that this performance can be obtained with optical spectral engineering and super forward error correcting code (FEC).

With the advent of coherent systems, the field of FECs has recently gained momentum. Up to now, the most common FEC in wavelength-division multiplexed (WDM) transmission systems at 10Gb/s and 40Gb/s bit-rates uses a concatenated code assuming hard-decision, with 7% overhead and a net coding gain (NCG) of ~8.5dB, leading to an FEC bit-error rate (BER) threshold of  $4 \cdot 10^{-3}$  [6]. An alternative hard-decision code, with 25% overhead, is also in operation over some commercial submarine cables at 10Gb/s and corrects a BER of  $1.3 \cdot 10^{-2}$  (7dB  $Q^2$ -factor). By comparison, a super FEC uses soft-decision FEC and can achieve more than 10dB of NCG. With a comparable overhead (23.6%) [7,8], such a FEC could correct BERs up to  $2 \cdot 10^{-2}$  (6.25dB  $Q^2$ -factor). It was demonstrated experimentally at 10Gb/s in 2003 [7], and realized in CMOS VLSI technology in 2006 [8]. It requires complex analog-to-digital converters at the receiver which, helpfully, are included in all coherent receivers. However, the benefits of super FEC cannot be evaluated only through the NCG and the maximum BER that can be corrected. They can be undermined by the increase of overhead, resulting in impairments from electronic components and in greater linear and nonlinear crosstalk from WDM channel neighbors. In our experiment, we assess the impact of these impairments by operating at 128Gb/s and 112Gb/s, to emulate super FEC and conventional FEC, with 7% and 23% coding and protocol overheads, respectively. Despite the very narrow channel spacing (37.5GHz), we achieve transmission over transpacific distance.

## 2. Experimental-setup

Our test-bed is depicted in Fig. 1. It involves 96 distributed feedback (DFB) lasers, ranging from 1533.47nm to 1561.83nm, spaced 37.5GHz apart, which are combined into two spectrally-interleaved wavelength combs. The two combs are passed into two separate QPSK modulators, fed with  $2^{15}$ -1 bit-long sequences at 32Gb/s, emulating 23%-FEC overhead and protocol overhead. A 3dB coupler splits the output of each modulator into two polarization-maintaining fiber paths, which are delayed by hundreds of symbols, before being recombined through a polarization beam combiner (PBC). This produces PDM-QPSK data at 128Gb/s. The odd and even channels are spectrally interleaved through a commercially available 37.5GHz optical interleaver with programmable transfer function. After the interleaver the optical comb is boosted by a dual-stage EDFA and is injected into the recirculating loop.

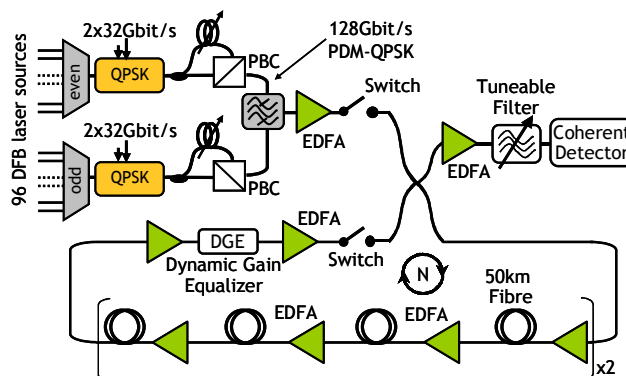


Fig. 1. Experimental setup

The loop consists of eight 50km spans of a new prototype fiber from Draka with an ultra-large effective area of  $155\mu\text{m}^2$ , an attenuation of  $0.185\text{dB/km}$  at  $1550\text{nm}$ , and a chromatic dispersion of  $21.7\text{ps/nm}\cdot\text{km}$  at  $1550\text{nm}$ . No dispersion-compensating fiber is used in the experiment. The loss of each span is compensated for by a single stage 980-nm pumped EDFA followed by a gain-flattening filter for channel-to-channel equalization. Further adjustment is performed with a dynamic gain equalizer, located between two EDFAs. Filling and emptying of the loop is controlled by two acousto-optic switches, triggered by time-delay generators, synchronously with the BER measurement equipment.

At the receiver end, the signal is pre-selected with a narrow tuneable optical filter and sent to the dual-polarization coherent receiver. The receiver is based on a real-time 50GSamples/s sampling scope with 16GHz bandwidth, interfaced with a computer for offline processing [9]. Chromatic dispersion of up to  $295\text{ns/nm}$  is digitally compensated for.

Waveform engineering is undoubtedly a promising field for performance improvement. We focused here on spectral engineering, targeting the largest filling ratio of the  $37.5\text{GHz}$  channel grid with  $32\text{Gbaud}$  signals. This suggests reshaping the spectrum of each channel to a square-like profile [10]. We adjust our programmable optical filter with  $34\text{GHz}$  bandwidth at  $25\text{dB}$  (i.e. with the steepest leading and trailing edges achievable with our equipment), while the top of the intensity response is engineered to follow a quadratic intensity profile of variable depth in dB.

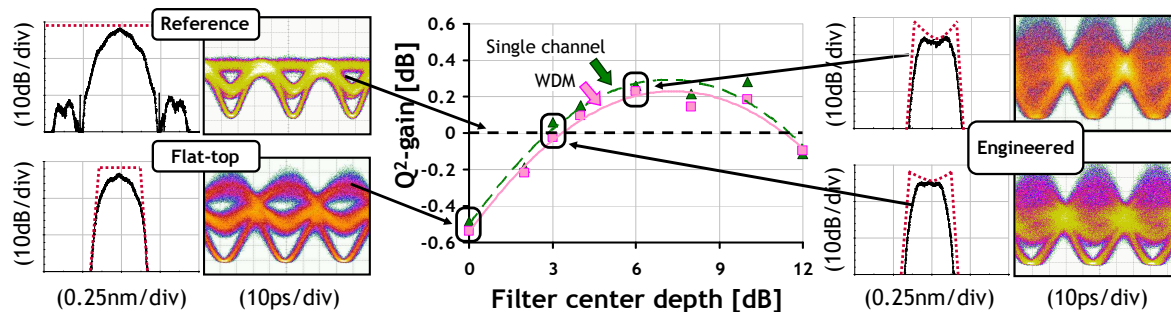


Fig. 2. Benefits of optical spectral engineering. In the insets, measured signal spectra (1pm resolution), filter power responses and eye-diagrams along one polarization.

### 3. Results

We measure the  $Q^2$ -factor of one typical channel in back to back with all WDM neighbors and normalize it to the reference  $Q^2$ -factor of the same channel without filter (actually, passed in a large noise-rejecting optical filter which induces with no noticeable signal truncation). This yields the so-called  $Q^2$ -gain, reported in Fig 2. The gain is measured when the filter centre depth is varied, whether the channel is surrounded by neighbors or not. It can be seen that the  $Q^2$ -factors are almost unchanged when the neighboring channels are removed, which shows that channel-to-channel crosstalk is well-contained in all filter configurations investigated here. Fig. 2 also depicts a few typical spectral profiles and the corresponding eye-diagrams of one polarization tributary, when surrounded by neighbors. One conclusion that can be drawn from the measurements is that the narrow profile of the standard flat-

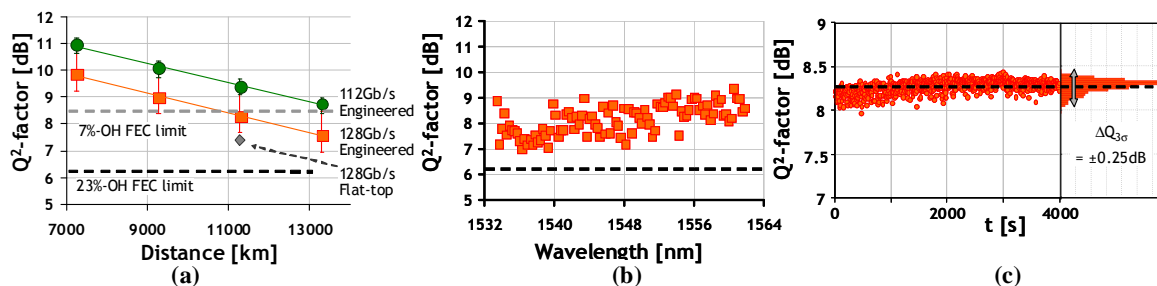


Fig 3. (a) Impact of FEC overhead on performance versus distance; (b) Q<sup>2</sup>-factors of all the 96 channels after 11,680km; (c) Statistics of Q<sup>2</sup>-factor over 4000s at 1547.31nm after 11,680km.

top filter is found responsible for 0.5dB penalty with respect to the no-filter reference. Engineering the spectral response according to a quadratic profile with variable depth enhances the power of the spectral components which are farther from the carrier frequency, and the Q<sup>2</sup>-factor can become larger than that of a single channel without optical filter. Interestingly, the optimum depth (at 6dB) was found identical in the back-to-back configuration of Fig. 2 and after transmission. We therefore chose this setting in the rest of the paper.

We feed the recirculating loop with the above signal at 18, 23, 28 and 33 loop round-trips corresponding to 7,250km, 9,270km, 11,280km and 13,300km. To evaluate the impact of the increased FEC overhead the measurements have been taken at 28GBaud and 32GBaud at these distances. We report in Fig. 3a the average performance (over a dozen channels) in the middle of the EDFA band versus distance at 112Gb/s (green circles) and 128Gb/s (red squares). A point at 11,280km (gray diamond) indicates the Q<sup>2</sup>-factor with a simple flat top filter at 128Gb/s. The average Q<sup>2</sup>-factor is 9.85dB and 10.95dB respectively at 128Gb/s and at 112Gb/s after 7,250km. It decreases down to 7.57dB and 8.75dB respectively after 13,300km. The impact of an FEC overhead increase from 7% to 23% is therefore in the range of 1dB, to be compared with the 0.6dB line rates ratio ( $10 \cdot \log(128/112)$ ). This Q<sup>2</sup>-factor degradation stays within acceptable limits despite the narrow channel spacing. Hence, the reduction of the Q<sup>2</sup>-factor FEC threshold (2.2dB) stemming from the use of 23%-overhead super FEC clearly outweighs the degradations due to crosstalk and propagation impairments. Note that no BER could be recorded without optical pre-filtering. Besides, the fine optical spectral engineering of Fig. 2 is found to provide a 1dB Q<sup>2</sup>-factor improvement at 11,280km distance. By simply extrapolating the curves of Fig. 3a, this improvement can be translated here into a valuable  $\sim 2500$ km gain on the propagation distance.

Fig. 3b shows the results obtained at 11,680km, where all the 96 channels have been measured. The average Q<sup>2</sup>-factor is 8.1dB and the worst Q<sup>2</sup>-factor across the WDM comb is 7.0dB, still 0.75dB above the FEC threshold. In Fig. 3c, we reported the statistics of Q<sup>2</sup>-factor recordings over 4000s for a typical channel, namely at 1547.31nm. The measurements are found very stable, with standard deviation below  $\pm 0.25$ dB.

#### 4. Conclusions

We have demonstrated a transmission of 96 x 100Gb/s 37.5GHz-spaced channels over 11,680km. We used coherent detection, polarization multiplexing, QPSK modulation format and ultra-large effective area fiber. The combination of 23% overhead FEC and optical spectral engineering enable the high spectral information density of 2.7b/s/Hz with minimal increase of propagation impairments. Therefore our experiment matches the best reported capacity times distance product (112Pb/s-km) while employing only C-band EDFAs.

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