Abstract—We show experimental results on the transmission of a Terabit superchannel, consisting of 10x120-Gb/s PM-QPSK densely-packed subcarriers. We reached 10,000 km with 1.1xBaud-rate subcarrier spacing and 9,000 km with Baud-rate subcarrier spacing. We also reached 8,000 km with 3 superchannels at 1.1 spacing. Moreover, using the same experimental setup, we investigated the estimation of channel parameters from the receiver equalizer taps after CMA, also showing long-term results of joint measurements of BER, DGD and PDL.

Keywords—Coherent detection, PM-QPSK, Terabit superchannel, PSCF, optical performance monitoring.

I. INTRODUCTION

Recently there has been an increasing interest in the investigation of 1Tb/s “superchannels” [1-3] in support of an eventual Terabit Ethernet Standard. According to this technique, a number of “subcarriers” are seamlessly aggregated to form individual superchannels which would be routed optically through the network as a single channel.

In [1] and [2] the subcarriers were electrically OFDM (Orthogonal Frequency–Division Multiplexing) modulated and the superchannel reached 600 and 400 km, respectively. In [3], 24 subcarriers were modulated using polarization multiplexed (PM) QPSK at 12.5 GBaud each. The subcarriers were spaced exactly the Baud rate and each subcarrier was frequency-locked and symbol transition-aligned to all others, thus realizing Coherent Optical OFDM (Co-OFDM). Using low-loss and Ultra Large Area Fibre (ULAF) in combination with Raman amplification, [3] reached a transmission distance of 7,200 km.

A possible alternative approach to Co-OFDM, to realize near-Baud-rate or Baud-rate spacing of subcarriers, is that of creating a superchannel by tightly packing conventional WDM subcarriers, while achieving low crosstalk by using subcarrier narrow optical filtering at the transmitter (Tx). This technique has been widely used in radio links for decades and has been recently proposed for optical links too [4-6]. This concept is sometimes called “Nyquist WDM”.

In this work, we experimentally investigate the long-haul reach of a Terabit superchannel using 10x(30GBaud) PM-QPSK subcarriers (1.2 Tb/s), with off-line processing. The spacing was set at either 33 or 30 GHz, that is, either 1.1 times the Baud rate or exactly the Baud rate. We also performed an experiment using 3 Terabit superchannels together. Overall, these different set-ups always reached at least 8,000 km, and in one case up to 10,000 km. Note that we decided to push the Baud rate to 30 GBaud, despite component bandwidth and sampling rate limitations, to be able to assume 20% FEC overhead, which appears to be the target overhead for second-generation PMQPSK transponders. Advanced hard-FECs with 20% overhead, with a threshold BER=10^-2, are currently being engineered. With the same overhead, soft-FECs could reach a substantially higher BER (2⋅10^-2 or greater). In this work we aimed at the hard-FEC threshold of BER=10^-2.
Using the same experimental set-up, we also investigate the use of advanced channel monitoring techniques, required by increasingly sophisticated high-capacity and long-distance optical networks [7]. One of the advantages of using polarization-multiplexed modulation formats together with polarization diversity coherent receivers (Rx) followed by digital signal processing (DSP), is the possibility of using the adaptive equalizer filter taps to monitor the characteristics of the transmission link. In fact, it has recently been demonstrated by simulations and short reach experiments that the Rx equalizer filter taps can be used to estimate chromatic dispersion (CD), differential group delay (DGD) and polarization dependent losses (PDL) [8–10]. In this work we demonstrate the use of channel estimation algorithms in a ultra-long-haul high capacity WDM transmission scenario.

II. DESCRIPTION OF THE EXPERIMENT

The experimental setup for the three superchannel experiment with 33 GHz spacing is shown in Fig. 1. Fifteen CW wavelengths spaced 66 GHz were modulated using a Nested Mach-Zehnder (NMZ) modulator, provided by OCLARO, to generate a 15-subcarrier signal, with each subcarrier carrying 60 Gb/s. This WDM signal was then narrow-filtered using a reconfigurable Finisar optical Waveshaper™ filter, with -3dB bandwidth 33 GHz. This filter is capable of generating all passbands at once, so only one filter unit was used. In addition to narrow filtering, the Waveshaper filter profile was set to enhance the high frequency components of each QPSK subcarrier (see Fig. 2) to pre-compensate for electrical bandwidth limitations both at the Tx and Rx. All fifteen 66-GHz spaced QPSK subcarriers were then launched
into an optical frequency-doubler, comprising a pass-through branch and a frequency-shifter (FS) branch. The latter included a NMZ modulator operated as a FS, configured to shift the fifteen input subcarriers by 33 GHz. The pass-through and FS branches were delayed for decorrelation and then combined to form a 30-subcarrier, 33-GHz spaced QPSK-modulated signal. This signal was then polarization multiplexed to form a 30-subcarrier PM-QPSK signal, with 33GHz spacing. Each PM-QPSK subcarrier carries 120 Gb/s. The Tx signal spectrum is shown in Fig. 3.

The signal was then launched into a recirculating fiber loop consisting of 98.1-km of uncompensated Z-PLUS® PSCF. The fiber loss is 17.6 dB. Nominal dispersion at 1550 nm is 20.6 ps/nm/km, slope 0.06 ps/nm²/km. The effective area is about 110 µm². Backward Raman amplification was used with a net gain of 9.2 dB. A three-pump Raman source with a total power of 800 mW was employed, at 1425, 1436 and 1459 nm. The loop included a dual-stage EDFA as well. A gain-flattening filter, the loop acousto-optic switch and the 3 dB coupler were inserted between the EDFA first and second stage.

The Rx had a standard set-up for coherent reception, with a LO and two 90-degree hybrids. The eight outputs of the two hybrids were detected using linear-amplified dual-balanced photodetectors with 30 GHz bandwidth provided by Linkrate-Teleoptix. Subcarrier selection was performed exclusively by tuning the LO. The four photodetectors electrical signals were digitized at 50GSa/s using a Tektronix DPO71604 real-time scope. The sampling rate was 1.66 samples/symbol. The measured scope analog -3dB bandwidth was only 12 GHz, i.e., 0.4 times the Baud rate. It was compensated for by Tx optical pre-emphasis, as mentioned, and by the Rx DSP equalizer.

The Rx DSP consisted of a CD-compensation first stage followed by a 25-taps MIMO stage adjusted through a decision-driven CMA algorithm, followed in turn by frequency estimation and a Viterbi&Viterbi stage. Tx and LO lasers were two distinct, external-cavity lasers (ECL), with linewidth of about 100 kHz. At the Tx, the ECL was tuned to each channel position, replacing each DFB source in turn, for BER measurements.

### III. EXPERIMENTAL RESULTS

Fig. 4 shows the back-to-back (btb) BER performance measured on the 16th channel. The required OSNR at BER=10⁻² was 13.7 dB, 2.6 dB from ideal. The maximum distance achieved with 30 subcarriers at BER≤10⁻² was 82 spans (8,044 km) at an optimal power per subcarrier of -4 dBm.

Fig. 5 shows the measured BER on each of the 30 subcarriers. Taking out FEC overhead, the net transmission rate was 3 Tb/s. We then repeated the experiment with just one 1.2 Tb/s superchannel (10 subcarriers). We reached 102 recirculations, or 10,006 km. The BER for all subcarriers is shown in Fig. 6. The reason for the longer reach of the single-superchannel was that the loop EDFA could not be optimized for the low-gain regime of mixed EDFA-Raman amplification. Its noise figure (NF) was about 7.5 dB when transmitting three superchannels and about 5.5 dB with a single superchannel.
The longer reach obtained with a single 1-Tb/s superchannel vs. three (10,006 vs. 8,044 km) was therefore mostly due to lower NF, rather than lower non-linear crosstalk.

IV. EXPERIMENTAL RESULTS AT BAUD-RATE SPACING

We then lowered the subcarrier spacing to 30 GHz, that is to the Baud-rate, and transmitted a single Tb/s superchannel. The Waveshaper bandwidth was reduced to 30 GHz. The btb sensitivity measurement over the 5th subcarrier showed a floor, due to crosstalk, of about BER=10^-4 (see Fig. 4).

Nonetheless, long-haul performance was marginally affected and a max-reach curve taken on the 5th subcarrier is shown in Fig. 7, for BER\leq10^{-2}, reaching 9,000km with an optimum launch power around -4.5 dBm per subcarrier. We measured BER on subcarriers 6th and 1st as well, which showed same and slightly better performance than 5th.

V. CHANNEL ESTIMATION RESULTS

For each of the thirty subcarriers, performance monitoring algorithms similar to those described in [9],[10] have been applied, after 8,000 km transmission (82 recirculations), to estimate CD, PMD, PDL and the electro-optical transfer function |H(f)|^2.

An example of the plots obtained for subcarriers 18 and 28 is shown in Fig. 8. The plots relative to the estimation of PDL, DGD and CD are shown only in the range [-15,15] GHz, since the values that fall outside the cut-off bandwidth of the Rx are not significant. The lower left plot shows the estimated electro-optical transfer function of the system. This plot can be used as an indicator of the correct tuning of the Tx laser and the optical shaping filter: if the passband of the filter is not centered at the laser emitting frequency, the plot of |H(f)|^2 is asymmetrical (see Fig. 8, dashed line).
Fig. 9 shows the values of CD measured for all 30 subcarriers, from which a slope of 0.057 ps/nm²/km can be extrapolated, which is very close to the nominal 0.06 ps/nm²/km reported in the datasheets.

Figs. 10 and 11 show the results of long-term measurements (several hours) in terms of DGD and PDL at \( f = 0 \) on the center channel (6th) of the single superchannel transmission with subcarrier spacing equal to the Baud rate. The values of measured BER are also shown for reference. We have verified through simulations that the monitor is able to estimate the correct PDL value regardless of the relative angle between the signal state of polarization (SOP) and the PDL axis, while the monitored DGD value depends on the direction of the signal SOP with respect to DGD vector (the estimated value may vary from 0 to the actual DGD). The variations of DGD in Fig. 11 are mainly due to this effect and consequently are not related to the value of BER, since DGD can be completely compensated for by the equalizer.

On the contrary, the estimated values of PDL in Fig. 10 correspond to the actual PDL present in the system at time of measurement and are strictly related to the values of BER: while the effects on PDL on the signal power variations can be compensated for by the equalizer, the performance is nevertheless degraded by the effects of PDL on noise. Note that such high values of PDL (up to 5-6 dB) are due to the specific transmission setup, made of a large number of recirculations of identical single-span links.

VI. COMMENTS AND CONCLUSION

We used the Waveshaper filter because of its easy reconfigurability. However, its measured profile was not particularly steep (approximately order-2 super-gaussian). Current technology can achieve steeper filters allowing Baud-rate spacing with lower crosstalk. Note that there is no need to use a separate filter for each subcarrier: Tx filtering can be performed for instance using interleavers [4],[6]. At the time when the results of this paper were being collected, experiment [6] reached 10,600km with spacing 1.2 Baud-rate and 4,368km at an impressive spacing 0.9.

Our results and [6] cannot be easily compared for various reasons: different number of carriers, different span length and amplification, different Baud-rate and assumed FEC redundancy, different target BER. Also, at spacing 0.9, [6] has substantial ISI and used MAP post-processing to mitigate it. All in all, we believe that both our results and [6] show that the "Nyquist WDM" concept together with PM-QPSK and coherent reception appear to allow extreme subcarrier packing, over ultralong-haul distances. It is therefore a promising technique for ultra-high spectral-density, ultralong-haul links.

Finally, we have also shown an experimental demonstration of channel estimation based on the use of coherent receiver equalizer taps in a ultra-long-haul high-capacity WDM transmission scenario, characterized by high values of PDL and DGD.

ACKNOWLEDGMENTS

We thank Sumitomo Electric Industries for providing the Z-PLUS® fiber. This work was supported by CISCO Systems (SRA contract) and by EUROFOS (‘Europe’s Research Network on Photonic Systems’), a Networks of Excellence funded by the European Commission through the 7th ICT-Framework Programme.
REFERENCES


