54.2 Tb/s Transoceanic Transmission Using Ultra Low Loss Fiber, Multi-rate FEC and Digital Nonlinear Mitigation

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Abstract *We demonstrate 54.2Tb/s transmission over transoceanic distances with an average channel rate above 300Gb/s and power consumption as low as 37.1pW/bit/s for the transmission line, thanks to ultra-low-loss fibers, multi-rate FECs and digital nonlinear mitigation techniques.*

Introduction

Recently, several transoceanic experiments using polarization division multiplexed 16-ary quadrature amplitude modulation (PDM-16QAM) over C+L band have been reported[1-5]. Erbium-doped fiber amplifiers (EDFA)[1-3], and hybrid Raman-EDFA[4,5] were used. Previous record transoceanic experiments (≥6,000km) report on channel bit rates of 250Gb/s or below (cf. Fig.1.a). In this work, we demonstrate a power efficient EDFA-only 178-channel PDM-16QAM transmission achieving 54.2Tb/s after 6,600km (~304.5Gb/s per channel). This is accomplished thanks to ultra low loss fibers, high performance CMOS digital-to-analog convertors (DAC), multi-rate forward error correcting codes (FEC) with a new rate optimization algorithm, and digital mitigation of fiber nonlinear impairments. We compare digital back- propagation (DBP) and perturbative nonlinearity post-compensation (PNLC), over the whole C+L band and for three distances, demonstrating, for the first time to the authors' knowledge, the efficiency of analytical formulae to adapt PNLC over a wide range of wavelengths and distances to provide similar gains as those of DBP.

Setup

Fig.1.b shows the transmitter. In C-band, eight 50GHz-spaced tunable laser sources were divided into even and odd rails, and independently modulated by two polarization-multiplexed IQ-modulators (PM IQ-MOD) to form the test comb, coupled through an 80/20 coupler, to 79 50GHz-spaced loading channels modulated by a third PM IQ-MOD. Loading channels were notch-filtered by a wavelength-selective switch prior to coupling to the test comb to emulate TX optical signa- to-noise ratio of a WDM terminal. Each PM IQ-MOD was driven by a DAC operating at 88GS/s. The L-band transmitter was similar to C-band, but with 83 loading channels. C- and L-band were multiplexed and injected into the recirculation loop. The total launched power was 22dBm. 49GBd PM-16QAM, with root-raised-cosine pulse-shaping with roll-off 0.01 was used. De-correlated binary De Bruijn sequences of length 2^{15} and 0.5% overhead pilot-assisted direct decoding was employed. This overhead was subtracted in net capacity calculations. Fig.1.c illustrates the recirculation loop, consisting of 12 spans, each composed of 55km of Corning® Vascade® EX3000 fiber having in average an attenuation of 0.157dB/km and an effective area of 150µm², and dual-band EDFA-only amplification. At the receiver, the signal was mixed with a local oscillator and sampled by an 80GS/s real-time scope with 33GHz bandwidth. Chromatic dispersion compensation, polarization de-multiplexing, carrier frequency and phase estimation, FEC and nonlinear

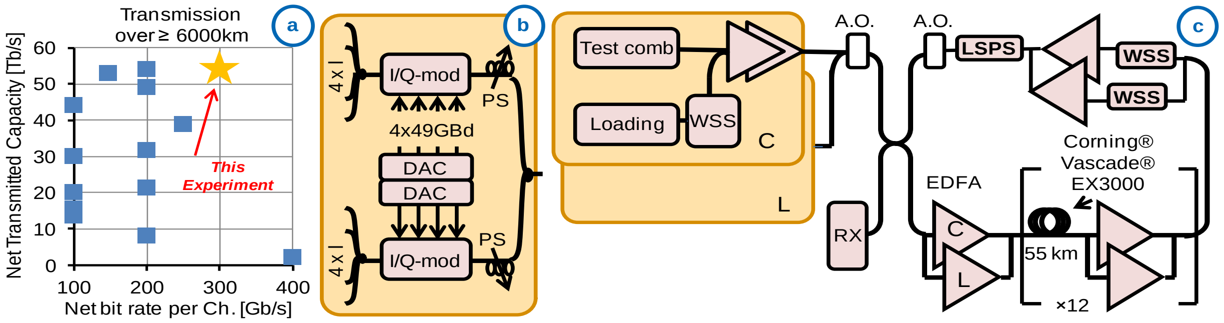

Fig. 1: a): Net capacity vs. channel net bit-rate of recent submarine experiments, b) transmitter setup, c) recirculation loop. DAC: digital-to-analog convertor, PS: polarization scrambler, WSS: wavelength selective switch, A.O.: acousto-optic switch, LSPS: loop synchronous polarization scrambler, EDFA: Erbium-doped fiber amplifier.

compensation were applied off-line.

Nonlinearity mitigation and FEC

Filtered DBP[8] and PNLC[9] were examined. For filtered DBP, one-step per two spans and 0.5-order super-Gaussian nonlinear phase filtering were used. For PNLC, the analytical results of[9] were employed to re-compute the perturbative coefficients for each wavelength and distance. Both DBP filter bandwidth and scaling coefficients for either DBP nonlinear phase correction or PNLC additive correction were optimized for each channel and distance.

Irregular spatially-coupled low density parity check codes with 10 iterations and length 15 windowed decoding were used as FEC[3,6,7]. A class of 52 FECs with rates uniformly spaced over the interval [0.4, 0.91] with steps of 0.01 were designed and used to decode all channels.

FEC rate optimization algorithm

Suppose we have N channels carrying the same raw bit-rate, and M available FEC rates: $r_1<....<r_M$. For any K between 1 and M we want to find the optimum rates $X_1<...<X_K$, where each X_i is one of the available FEC rates, such that if only these optimum rates are employed to decode the N channels, the total net capacity is maximized. This problem has a geometric interpretation, illustrated in Fig.2.a for $K = 4$. Suppose we have processed each channel separately with all M available FEC codes, and obtained a function $F(r)$ vs. r, where $F(r)$ is the number of error-free decoded channels with rate r. Consider the graph of $F(r)$ vs. r in Fig.2.a. For any K, the total net capacity is equal to the shaded area of the piecewise constant approximation of F defined by selected rates. The set of optimum rates maximize this area[10]. To find the optimum we first notice that the problem has an equivalent trellis representation, shown in Fig.2.b. The corresponding trellis starts at the 'beginning' state B at step $k = 0$, and ends in 'end' state E at step $k = K+1$. For $k = 1,...,K$, the trellis has M states, $S_1, ...,S_M$, where S_i corresponds to adopting the rate r_i at step k. Transition from B to any state, and from any state to E is allowed; otherwise, transition from any S_i at step k, ($k = 1,...,K-1$), to any state S_j at step $k+1$ is allowed only if $j>i$. We define the transition weight between two states as follows: $w(S_i,B)= r_iF(r_i)$, $w(E,S_i)= 0$, and $w(S_j,S_i) = (r_j-r_i)F(r_j)$ only if $j>i$. , where $w(final,initial)$ is the transition weight from *initial* to *final* state. Now, maximizing the surface of the piecewise constant approximation of F is equivalent to finding the maximum weight path between B and E on the equivalent trellis. We apply Viterbi algorithm to find such a path. In this work, for each distance we had $N = 178$, $M = 52$, and $r_m = 0.39+0.01m$, for $m = 1,...,M$. For each $K = 1,...,M$ an optimization problem is solved.

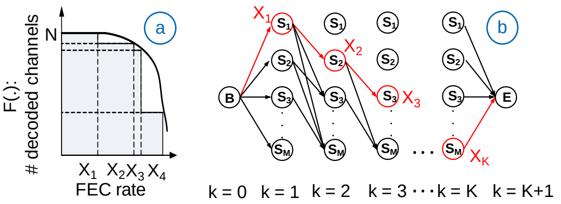

Fig. 2: a) Geometric interpretation of FEC rate optimization problem, b) Equivalent trellis representation.

Results

Fig.3.a illustrates pre-FEC Q^2 [dB] of 87 C-band, and 91 L-band channels measured after 10, 12 and 14 loops, (6,600, 7,920 and 9,240 km) without applying fiber nonlinearity mitigation. The gain in Q^2 [dB], after 6,600 km, by either DBP or PNLC is shown Fig 2.b. Similar gains were obtained even if DBP slightly outperformed PNLC. Depending on the implementation, PNLC can be one to two orders of magnitudes less complex than DBP with similar gains Each measured channel is then decoded with 52 different FECs to extract the highest capacity from each channel. The maximum net post-FEC capacity after Multi-rate optimization, transported as a function of distance is given in Fig 3.c. A total capacity of 54.2Tb/s is transported at 6,600km using DBP.

Fig. 4 shows the optimized net capacity vs. number of allowed rates, without and with nonlinearity compensation. The net capacity rapidly increases when the number of allowed rates increases from 1 to 4, and then slowly tends to its maximum value.

Another aspect studied is power feeding of undersea cables, a challenging issue of high capacity and long-haul systems. We used high efficiency EDFAs instead of Raman amplification which might provide higher performance but at the expense of higher power feeding requirements. In [4], the power requirements of hybrid C+L Raman-EDFA were twice as an C+L EDFA-only system.

We monitored the current and the required voltage for each EDFA pump to evaluate the power consumption of the transmission line. On average, L-band pump power consumption was 44% higher than that of C-Band for 19dBm output power, with gain flattening filters placed at EDFAs output. No power requirement for temperature control was considered as undersea systems are passively cooled by ocean water. An additional 1.5V voltage drop

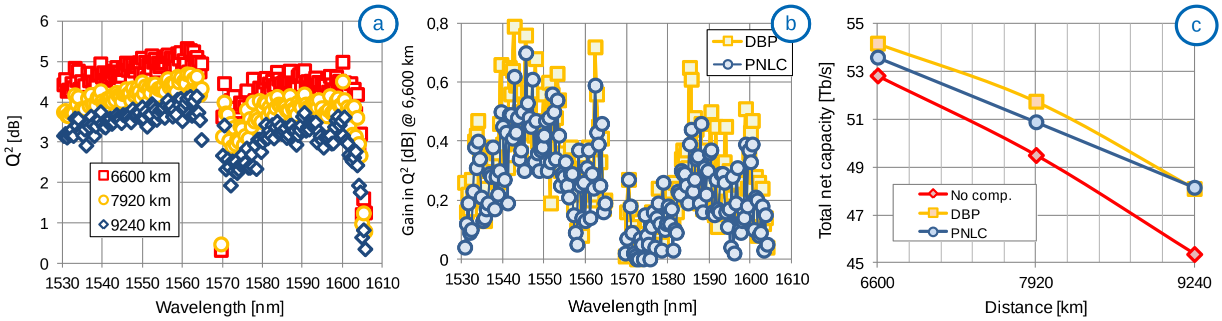

Fig. 3: a): Pre-FEC Q^2 without nonlinear compensation, b) Gain in Q^2 of digital backpropagation (DBP), and perturbative nonlinearity post compensation (PNLC), c) Total net capacity vs distance with and w/o two nonlinearity compensation methods.

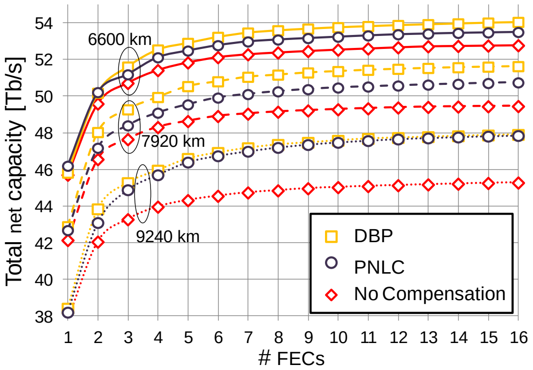

Fig. 4: Optimized total net capacity vs. number of FECs.

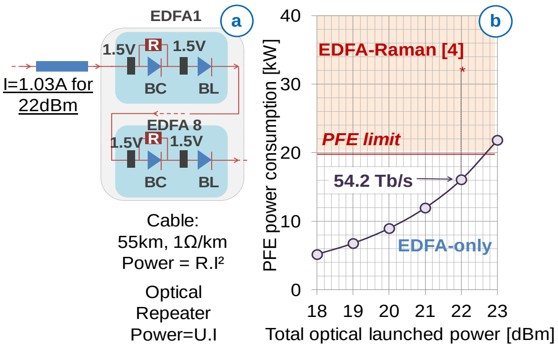

Fig. 5: a) Power consumption model, b) power feeding equipment (PFE) consumption vs. launched power.

per pump was considered for pump control and supervision. The equivalent circuit corresponding to a single span is given in Fig. 5.a. Assuming a 6600km-long system composed of 4 bidirectional fiber pairs with serially connected pumps, the total consumed power was computed and plotted vs. optical launched power Fig. 5.b. At 22dBm (19dBm for each band), the power consumption reaches 16.1kW, enabling the transmission of 54.2Tb/s per fiber, using DBP, resulting in 37.1pW/bit/s power efficiency for a 4-pair link. Given the current technology, providing more than 20kW is challenging. Note that the copper cable consumed almost 45% of the total electrical power for 22dBm output optical power.

Conclusions

We reported on transmission of 178 channels of 49Gbaud EDFA-only PDM-16QAM with 50GHz spacing over transoceanic distances more than or equal to 6,600 km. Digital back-propagation and perturbative nonlinear post-compensation were optionally applied and their pre-FEC and post-FEC benefits were compared. We achieved a total net capacity of 54.2Tb/s over 6,600km, corresponding to an average of 304.5Gb/s per channel, equivalent to 6.09 bits/s/Hz. As electrical power feeding of high capacity undersea cables is more and more challenging, we used power efficient EDFA-only (C+L)-band amplification and monitored line electrical power consumption. Assuming 4 fiber pairs power consumption was 16.1 kW, i.e., 37.1pW/bit/s.

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