Capacity Approaching Transmission using Probabilistic Shaping and DBP for PFE Constrained Submarine Optical Links

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Abstract *Probabilistic constellation shaping and DBP enables the reduction in per-channel launch power by 2.2 dB, in a 150 channel 11000 km submarine link. For a fixed PFE voltage of 12 kV, the total system throughput is increased by 64%.*

Introduction

The combination of advanced multi-level modulation formats, spectral shaping and forward error correction (FEC), is an essential requirement for optical communications systems to achieve high spectral efficiency (SE) and high sensitivity in a single fibre core. For submarine optical systems, the ultimate throughput (in bits per second) of the optical link is limited by the maximum voltage of the power feed equipment (PFE) required for the submerged repeaters that are placed periodically along the link[1]. For a fixed PFE voltage (V_{PFE}), the key to maximising system throughput hinges on the choice of modulation format, code rate, channel spacing and crucially, the optimum distribution of optical power among a number of parallel fibre pairs.

In this paper, an analytical approach is used to determine the increase in the total system throughput due to the use of digital back-propagation (DBP) and probabilistic constellation shaping (PS), in a 150 channel quasi-Nyquist spaced 32 GBd DP-64QAM system, with a transmission distance of 11000 km. It is shown that the optimum launch power per-channel is increased by ~1 dB using single channel DBP (SC-DBP), however for a fixed V_{PFE}, the total system throughput is maximised by using SC-DBP and PS to reduce the launch power, which enables an increase in the number of supported fibre pairs. This optimisation increases system throughput by 64%, relative to when only conventional electronic dispersion compensation (EDC) is employed.

Analytical Model

The signal-to-noise ratio (SNR) for the 11000 km submarine system was calculated using the parameters shown in Table 1 and using the following formula based on the Gaussian noise model[2]:

Tab. 1: System Parameters

Parameter Description	Value
Link length (L)	11000 km
Span length (L_s)	50 km
Number of spans (N_s)	220
Fibre loss (α)	0.16 dB/km
Fibre dispersion (D)	20 ps/nm.km
Fibre non-linear coefficient (γ)	1.2 W^{-1}/km
Number of channels (N)	150
Symbol rate (F_b)	32 GBd
RRC filter roll-off	0%
Channel spacing	32.3 GHz
EDFA noise figure	4.5 dB
Number of repeaters (n_r)	219
PFE cable resistance (R_o)	1 Ω/km
Power conversion efficiency (η_c)	5%

$$\mathrm{SNR_{DBP}} \approx \frac{P}{N_s P_{ASE} + \sigma_{ss}^2 + \eta\zeta P_{ASE} P^2} \quad (1)$$

where,

$$\sigma_{ss}^2 = \left[\eta(B) N_s^{(1+\epsilon_1)} - \eta(B_{DBP}) N_s^{(1+\epsilon_2)}\right] P^3 \quad (2)$$

is the signal-to-signal non-linear interference term, ϵ_1 is the coherence factor for the transmitted bandwidth (B), ϵ_2 is the coherence factor for the back-propagated bandwidth (B_{DBP}), ζ is a factor depending on the number of spans and the method used for digital non-linearity compensation[3], $G = L_s \cdot \alpha$ is the amplifier gain and $P_{ASE} = G \cdot NF \cdot h\nu \cdot B$ is the power of the amplified spontaneous emission (ASE) noise, where $h\nu$ the photon energy. The received SNR of the central wavelength division multiplexed (WDM) channel was estimated for a range of per-channel launch powers (P) from −18 dBm to 4 dBm.

For EDC only, the DBP bandwidth (B_{DBP}) is set to zero, therefore the non-linear interference term σ_{ss}^2 is at a maximum. In order to mitigate

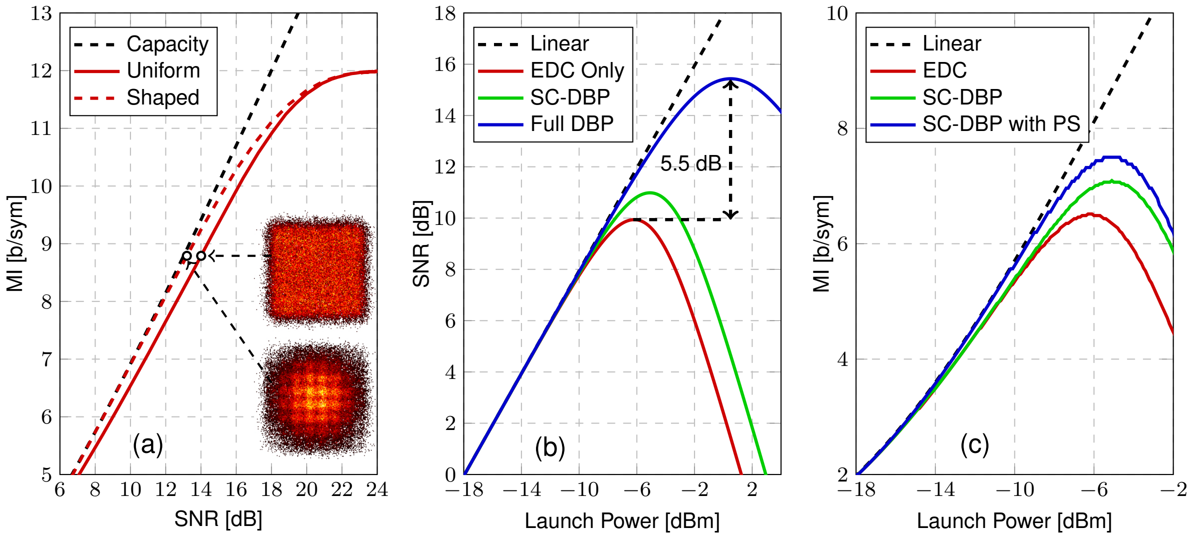

Fig. 1: (a) B2B MI as a function of received SNR for uniform and probabilistically shaped DP-64QAM. (b) Received SNR of the central WDM channel as a function of per-channel launch power after propagating over the 11000 km link, for EDC only, SC-DBP and full-field DBP. (c) Corresponding MI as a function of launch power for EDC only, SC-DBP and SC-DBP with PS.

for the non-linear distortion, B_{DBP} was swept from 32.3 GHz for SC-DBP, up to the full 4.845 THz bandwidth for full DBP. The received SNR obtained through Eq. 1 was subsequently translated to mutual information (MI) assuming an additive white Gaussian noise (AWGN) channel[4].

The minimum required PFE voltage was calculated by first computing the electrical power required for each repeater (P_r)[5]:

$$P_r = \frac{2N_{fp}NP}{\eta_c} + P_o \tag{3}$$

where N_{fp} is the number of fibre pairs and P_o is the power consumption of any control equipment not related to optical power conversion and was assumed to be 10% of P_r. The minimum V_{PFE} was subsequently calculated through: $V_{PFE} = 2\sqrt{R_c n_r P_r}$, where R_c is the total cable resistance defined as: $R_c = N_s R_o L_s$.

Received SNR and MI

Fig. 1 (a) illustrates the single channel back-to-back (B2B) MI (measured over two polarisations) as a function of received SNR for the DP-64QAM modulation format, with uniform and probabilistic constellation shaping[6]. An SNR sensitivity gain of more than 0.5 dB is observed for a wide range of received SNR values from 7.5 dB up to 17.5 dB. The maximum gain in sensitivity of ~0.8 dB was achieved at a received SNR of 13.2 dB for the probabilistically shaped constellation (with the corresponding constellation shown inset, at the bottom of Fig. 1 (a)).

The received SNR of the central WDM channel as a function of the launch power per-channel is shown in Fig. 1 (b). The dotted line is for reference only and illustrates the transmission performance for the linear channel. For EDC only, a maximum SNR of 9.9 dB was achieved at the optimum launch power of −6.2 dBm. As the launch power increases, the SNR performance sharply degrades due to fibre non-linearity. For SC-DBP (32.3 GHz), the received SNR increases by 1 dB due to the partial mitigation of fibre non-linear distortion, however this is only realised at a higher optimum launch power of −5.1 dBm. In the unrealistic case of a 150 WDM channel DBP, the peak-to-peak SNR increases by 5.5 dB, relative to the EDC only case. This is a substantial increase in SNR, however full-bandwidth DBP is not currently feasible due to the requirement of a coherent receiver with an optical bandwidth of 5 THz. In addition, the significant increase in optimum launch power by 6.7 dB is not practical for a PFE constrained submarine optical system. Therefore, the remainder of this paper will only consider SC-DBP for non-linearity mitigation.

The corresponding MI as a function of the launch power per-channel is shown in Fig. 1 (c). An MI of 6.5 b/sym was achieved at the optimum launch power when only EDC was employed. This increased to 7.1 b/sym when SC-DBP was included, which was further increased to 7.5 b/sym with the addition of probabilistic constellation shaping. Therefore, the MI was increased by 1 b/sym, however as mentioned previously, this was only realised for a higher channel launch power of −5.1 dBm. Conversely, for a fixed MI of 6.5 b/sym, which was the maximum achieved when only EDC was used, the launch

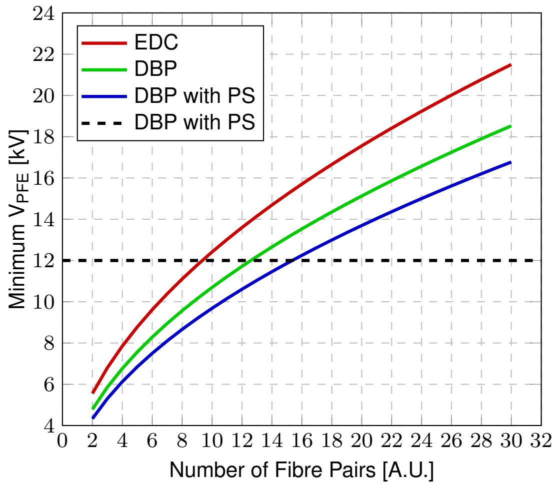

Fig. 2: Minimum PFE voltage as a function of the total number of fibre pairs. Dotted line at 12 kV reference.

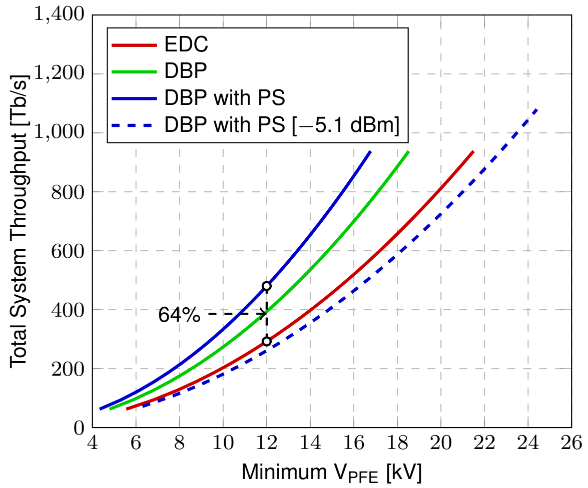

Fig. 3: (a) Total system throughput as a function of Minimum PFE voltage.

power is reduced by 2.2 dB, from −6.2 dBm to −8.4 dBm. This reduction in channel launch power, for a fixed MI, is very beneficial in a PFE constrained submarine link, as it can be exploited to achieve linear increases in throughput by increasing the number of supported fibre pairs within the submarine cable.

Minimum required V_{PFE}

Fig. 2 illustrates the total number of fibre pairs the 11000 km submarine link could support for a give PFE voltage. For the EDC only case, the systems operated at the optimum launch power of −6.2 dBm. At a reference PFE voltage of 12 kV, the system could support 9 fibre pairs. With the addition of SC-DBP, where the system operated at a reduced launch power of −7.5 dBm (for fixed MI of 6.5 b/sym as shown in Fig. 1(c)), the number of supported fibre pairs increased to 12. Finally, when both SC-DBP and PS was used, the system operated at a channel launch power of −8.4 dBm, which resulted in a further increase in the number of supported fibre pairs to 15.

The total system throughout as a function of the minimum required PFE voltage is shown in Fig. 3. A greater system throughput is achieved as the PFE voltage is increased, which is due to the addition of a greater number of fibre pairs. For the EDC only case, a total system throughput of 292.4 Tb/s was achieved at a minimum V_{PFE} of 12 kV. However, by using SC-DBP and probabilistic constellation shaping, which enabled a reduction in launch power for a fixed MI, the total system throughput increased to 480.4 Tb/s for the same minimum V_{PFE} of 12 kV. This represents a significant increase in throughput of 64% relative to the EDC only case.

Interestingly, from Fig. 3, it is evident that if the system operated at a launch power of −5.2 dBm, which corresponded to the optimum launch power when using SC-DBP, the total throughput would be ultimately lower that even the EDC only case. This is due to the fact that an increase in launch power of 1 dB per WDM channel only provided an increase in MI of 1 b/sym. However, by using SC-DBP and PS to achieve capacity approaching transmission at a reduced channel launch power, linear increases in throughput could be achieved by increasing the number of parallel fibre pairs.

Acknowledgements

The support under the UK EPSRC Programme Grant UNLOC (UNLocking the capacity of Optical Communications) EP/J017582/1 is gratefully acknowledged.

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