Power Optimization Strategy for Multi-Band Optical Systems

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Abstract *We propose a novel strategy which optimizes the power of all amplification bands in a Multi-Band system concurrently. The proposed method improves the OSNIR performance in S-band of more than 4 dB compared with optimization schemes in the literature.*

Introduction

The international "race" for 5G deployment in order to support the new wave of technologies and applications has put optical transport networks under significant strain. In order to underpin the demands of the 5G ecosystem, the spectrum of the optical fiber beyond C-band could be exploited. The main interest is focused on the low-loss attenuation frequencies of Single Mode Fiber (SMF) which span between 1260 nm and 1625 nm and they are segregated into "five" nominal amplification bands (O, E, S, C and L)[1]. In this context, power optimization can significantly improve the signal quality which can in turn enable a) the use of a higher-level modulation format, leading to higher transportation capacity or b) the extension of transparent reach, relaxing the needs for OEO regeneration in the network.

To date, power optimization strategies have been mainly confined to the C-band[2]-[5] and to a lesser extent to the C and L-bands[6],[7]. These techniques are efficient when the inter-band interactions caused by Stimulated Raman Scattering (SRS) are either compensated or ignored. However, when two or more bands are fully populated, SRS can lead to a severe performance degradation in the S-band and thus its impact cannot be neglected. In this paper, we propose a novel power optimization strategy which optimizes the power in all bands concurrently. This way, the Optical Signal to Noise plus Interference Ratio (OSNIR) performance of the channels in the S-band can be increased by more than 4 dB compared to a strategy allocating equal power per channel in all bands.

System Under Study

The system under investigation is British Telecom's (BT) "21st Century Network" (21CN)[8]. The transmission performance is estimated for the longest path of the network (Fig.1) assuming that all bands are fully loaded with channels which is the worst possible case in terms of physical layer performance. The path, link and span lengths are set to 1050, 150 and 50 km, respectively, whilst the transit part of each node employs Variable Optical Attenuators (VOAs). In this way it is ensured that the power at the beginning of the first link is the same as the power at the beginning of any other link.

Following reference[9], the employed amplification scheme is detailed in Tab. 1. The S-band is split into S_1 and S_2 sub-bands since a single Thulium Doped Fiber Amplifier (TDFA) cannot ensure sufficient power per channel at its output (higher than -2 dBm), due to the large amplification range (around 55 nm). The band mux-demux losses are estimated to be 2 dB in total, thus the amplification gain of each DFA equals the fiber loss of each band plus 2 dB.

Tab. 1: Band Partitioning used in our study

	Used Range (nm)	Number of channels	Noise Figure (dB)	Amplifier Type
S_1 band	1455-1480	92	5.5	TDFA
S_2 band	1485-1510	89	5.5	TDFA
C band	1530-1565	116	5.5	EDFA
L band	1570-1615	141	6.0	EDFA

Physical Layer Modelling

Under the assumption that FWM is a Gaussian Noise source, statistically independent from Amplified Spontaneous Emission (ASE) noise, the OSNIR is given by[10]:

$$OSNIR = \frac{P_{ch}}{P_{ASE} + P_{FWM}} \quad (1)$$

with P_{ch} the power of the examined channel, P_{FWM} the power of Four Wave Mixing (FWM) interference and P_{ASE} given by

$$P_{ASE} = \sum_{l=1}^{N_l} \left[\sum_{i=1}^{N_{s,l}} \left[hf\left(NF_i \cdot G_i - 1\right) B_0 \prod_{r=i+1}^{N_{s,l}} G_{SRS,\mathrm{r}} \right] / \left(\prod_{m=1}^{N_{s,l}} G_{SRS,m} \right) \right] \quad (2)$$

where G_i is the amplifier gain and NF_i is the

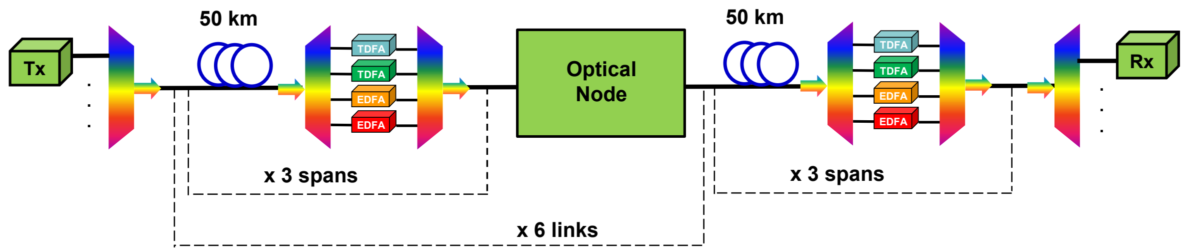

Fig. 1: System under study. The longest path of the BT's 21CN is considered.

noise figure at the i[th] amplification stage. N_l is the number of links forming up a path and $N_{s,l}$ the number of fibre spans of a link, equal to 7 and 3 in our case, respectively. In addition, we assume an optical bandwidth equal to 32 GHz and a channel spacing equal to 37.5 GHz.

FWM can be divided into two parts: intra-channel and inter-channel FWM. Intra-channel FWM is caused by the interactions between the frequencies of the observed channel only, whilst inter-channel FWM is caused by the interactions between the observed with all other channels. The proposed formalism was selected since it accounts for different power levels between the channels, an important prerequisite in a power optimization mechanism. Expanding[10], we have

$$P_{FWM,intra} = \frac{32}{27}\frac{\gamma^2 L_{eff}{}^2 P_{ch}{}^3 N_s{}^2 c}{\lambda^2 B^2 D\sqrt{z_1}}\left(1+\frac{4e^{-aL}}{\left(1-e^{-aL}\right)^2}\right) asinh\left(\frac{\pi\lambda^2 DB^2}{8c}\sqrt{z_2}\right) - \frac{32}{27}\frac{\gamma^2 L_{eff}{}^2 P_{ch}{}^3 N_s{}^2 c}{\lambda^2 B^2 D\sqrt{z_1+12L^2}}\frac{4e^{-aL}}{\left(1-e^{-aL}\right)^2} asinh\left(\frac{\pi\lambda^2 DB^2}{8c}\sqrt{z_2+12L^2}\right) \tag{3}$$

$$P_{FWM,inter} = \sum_{n=-\frac{N_{ch}-1}{2},\, n\neq 0}^{\frac{N_{ch}-1}{2}} P_n^2\left(1-\frac{5}{6}\Phi_n\right)\left|Log\left(\frac{n+1/2}{n-1/2}\right)\right| \times \frac{32}{27}\frac{\gamma^2 L_{eff}{}^2 P_{ch} N_s{}^2 c}{\lambda^2 B^2 D}\left(\frac{1}{\sqrt{z_1}}\left(1+\frac{4e^{-aL}}{\left(1-e^{-aL}\right)^2}\right)-\frac{1}{\sqrt{z_1+12L^2}}\frac{4e^{-aL}}{\left(1-e^{-aL}\right)^2}\right) \tag{4}$$

where $z_1 = \left(\frac{2}{a}\right)^2 + 2L^2\left(N_s{}^2-1\right)/\left(\sum_{k=x_1}^{x_2}\frac{1}{1+\left(2k\pi/(aL)\right)^2}\right)^2$,

$$x_1 = -\frac{\lambda^2 B^2 DLN_{ch}{}^2}{16c},\ x_2 = \frac{\lambda^2 B^2 DLN_{ch}{}^2}{2c},\ z_2 = \left(\frac{2}{a}\right)^2 + 2L^2\left(N_s{}^2-1\right)$$

with x_1 and x_2 rounded to the nearest integer less than or equal to their values. Index n includes all co-propagating channels of the link and takes values within the range $-\left(N_{ch}-1\right)/2 \le n \le \left(N_{ch}-1\right)/2$ where N_{ch} is the total number of channels within the band. P_n denotes the power of the n^{th} interfering channel, respectively. L is the span length, and Φ_n is a modulation format depended parameter[10].

In order to estimate the SRS Gain/Loss effect for the j[th] wavelength in the i[th] fibre span, we employ the expression of[11],[12]:

$$G_{SRS,i} = P_{tot,SRS}\frac{e^{\frac{g'\cdot B\cdot L_{eff}}{2A_e}(j-1)P_{tot,SRS}}}{\sum_m\left[P_{m,0}\, e^{\frac{g'\cdot B\cdot L_{eff}}{2A_e}(m-1)P_{tot,SRS}}\right]} \tag{5}$$

where g' is the Raman gain slope, equal to 4.9.10[-27] m/(W·Hz), A_e the effective cross sectional area of the fibre equal to 80 μm² and $P_{m,0}$ is the power of the m[th] interfering channel at fibre input. The term $P_{tot,SRS} = \sum_m P_{m,0}$ sums the power of the channels that interact within the SRS gain bandwidth, which is 15 THz, using the triangular approximation[13]. This wide SRS Gain bandwidth makes the OSNIR of one band a function of the power level of the channels in all other bands. Finally, secondary effects, like the impact of SRS on FWM, are ignored, a necessary simplification in order to complete the power optimization in reasonable time.

Proposed Power Optimization Strategy

The proposed optimization strategy is given by

$$\begin{aligned} &A\left(P_{S_1},P_{S_2},P_C,P_L\right) = \sum_b\left(\frac{1}{OSNIR_b\left(P_{S_1},P_{S_2},P_C,P_L\right)}\right)^2 \\ &minimize\ A\left(P_{S_1},P_{S_2},P_C,P_L\right) \\ &subject\,to\ \ P_{\min} \le P_{S_1},P_{S_2},P_C,P_L \le +1dBm \end{aligned} \tag{6}$$

where P_{S_1},P_{S_2},P_C,P_L represent the power of the middle channel of S_1, S_2, C and L-bands at the beginning of each link, respectively. The summation is done over the set $b=\{S_1, S_2, C, L\}$. Via the adopted method, a more balanced OSNIR performance is feasible across the entire spectrum by selecting the appropriate values of the power per band allowing them to swing between ASE-limited and NL-limited regimes: OSNIR in the L-band is traded for better OSNIR in the S-band counterbalancing SRS's impact.

The power constraints are set in Eq.(6) in order to ensure that the power per channel will: a) not be smaller than a P_{min} value, i.e. -6 dBm, which could lead to severe OSNR degradation and b) not be larger than +1 dBm, which would make the total power of the band exceed the maximum attainable output power of a DFA.

Results

The proposed strategy (“Strategy 1”) is benchmarked in Fig.2 against a) an iterative power optimization process[14] (“Strategy 2”) and b) a strategy allowing for equal power per channel in all bands (“Strategy 3”). As seen in Fig. 2, a policy for equal power per channel leads to a poor OSNIR performance especially in the S-band, however, this strategy is the least computationally complex. Secondly, we can observe that the iterative “Strategy 2” outperforms “Strategy 3” in C and L bands whilst it fails to achieve improved performance in the S-band, which can hardly attain an OSNIR value of 11 dB. Thirdly, “Strategy 1” clearly provides superior OSNIR performance in S_1 and S_2 bands compared to “Strategy 2” and “Strategy 3” whilst it shows performance in C and L bands comparable to “Strategy 3”.

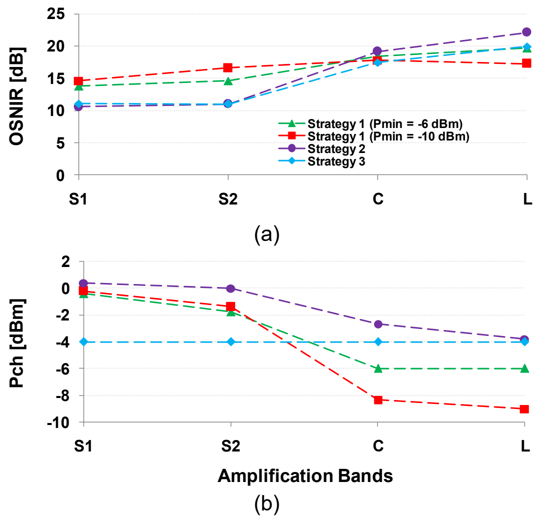

Fig. 2: OSNIR for different amplification bands and the corresponding power per channel attained using the three power optimization strategies.

The significant increase in OSNIR performance attained with our strategy can directly lead to an increased transportation capacity per channel by employing a higher modulation format. For example, channels with (polarization multiplexing) PM-QPSK can be upgraded to PM-16QAM or PM-32QAM.

In order to quantify the potential gains across a network, the three optimization strategies are applied in the BT’s 21CN[8] that comprises 22 nodes, resulting in a total of 231 different optical paths. The steps in our network study are as follows. First, the shortest path in all 231 cases is calculated. Second, the OSNIR for each path is estimated, using the channel powers of Fig.2b and assuming fully loaded links. Finally, the number of paths which clear the OSNIR thresholds for PM-16QAM (Fig.3a) and PM-32QAM (Fig.3b) are calculated for each band. The baud rate is set to 32 Gbaud resulting to data rates of 200 Gb/s and 300 Gb/s for PM-16QAM and PM-32QAM, respectively. Finally, the OSNIR thresholds for a target BER of 10^{-3} are set to 16.55 dB for PM-16QAM and to 19.5 dB for PM-32QAM.

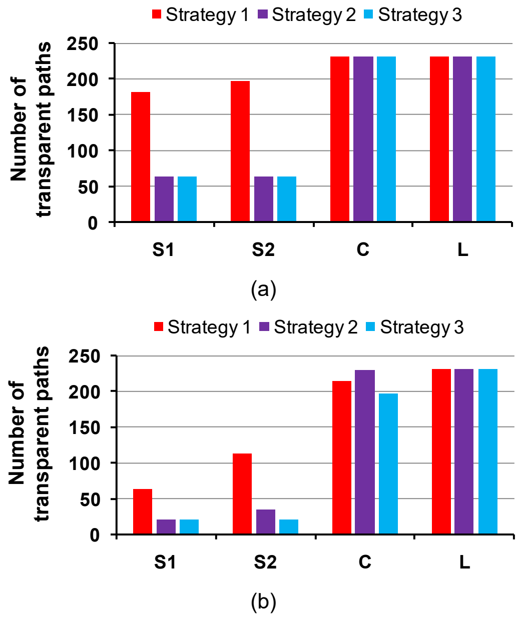

Fig. 3: Number of attainable transparent paths in BT’s 21CN employing a) PM-16QAM and b) PM-32QAM

As is evident from Fig.3, “Strategy 1” attains three times higher PM-16QAM and PM-32QAM transparent paths in S-band compared with the other two strategies. On the other hand, L-band can successfully support PM-16QAM and PM-32QAM in all transparent paths. Finally, C-band manages to inter-connect transparently all 22 nodes when PM-16QAM is employed while, in the case of PM-32QAM, it can support more than 92% of the paths using “Strategy 1”. The increase in the number of transparent paths using the proposed strategy can significantly reduce the need to deploy and operate costly OEO regeneration mechanisms.

Conclusions

We have proposed and validated a novel method to optimize the launch power per band of an optical multi-band transmission system. As a result, a balanced OSNIR performance is attained across the entire spectrum leading either to i) a three-fold increase in the available transparent paths; or b) higher transportation capacity for the S-band as the improved OSNIR performance makes feasible the implementation of higher modulation formats.

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