Connectivity Challenges in E, S, C and L Optical Multi-Band Systems

D. Uzunidis[(1)], C. Matrakidis[(1)], E. Kosmatos[(1)], A. Stavdas[(1)], P. Petropoulos[(2)], A. Lord[(3)]

[(1)] OpenLightComm Ltd, The Ross Building, Adastral Park, Ipswich, IP5 3RE, UK
[(2)] Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
[(3)] Applied Research, BT, Polaris House, Adastral Park, Ipswich, IP5 3RE, UK

Abstract: *Connectivity in Multi-Band networks depends on the attainable optical performance for a number of system-level parameters like number of channels, modulation format and symbol rate. We present three connectivity schemes engaging E, S, C and L bands. Exploiting a rigorous OSNIR optimisation method we tabulate their optical reach and the corresponding performance trade-offs.*

Introduction

With the advent of 6G, capacity and connectivity needs on the fixed-line network will soar due to the higher traffic volume and the unpredictable and more dynamic traffic patterns. Therefore, the exploitation of Optical Multi-Band (OMB) transmission[1],[2] becomes unavoidable since transmission within the C-band only means that as higher line-rates consume more optical bandwidth per channel, there will be fewer available channels in their number. Hence, capacity will be traded with connectivity.

The most critical factor for node connectivity in the context of Wavelength Routed Networks (WRN) is the number of the available wavelength channels and OMB transmission will ensure for flatter network architectures without needing to trade capacity for connectivity. In this work, we are considering an OMB system with > 200 nm of bandwidth (1410-1615 nm) exploiting the E, S, C and L bands. With the introduction of the E-band, it becomes evident that nonlinearities (NLs) and in particular inter-band effects, such as stimulated Raman scattering (SRS), play an increasingly dominant role to the overall OMB system performance. Moreover, NLs may severely degrade the performance of the already deployed channels[3],[4].

Therefore, such wideband OMB systems should be engineered adopting radically different methods compared to those in the C-band only systems era. In[1],[5], we have shown the importance of the optimal launched powers to attain a balanced operation between the ASE-limited and NL-limited bounds. Here, aiming to maximize the available number of channels, we study three alternative approaches: a) to optimize the launch power using the method of [5] that still leads to a considerable variation on the attainable optical signal to noise plus interference ratio (OSNIR) performance; b) to attain an as flat OSNIR performance as possible (e.g. < 1 dB variance) across the entire spectrum; c) to assume a differentiated reach policy with two zones of optical bands of < 1 dB OSNR variance within them. Given the Shannon limit, these alternatives lead to a different optical reach performance as a function of symbol rate and modulation format. Next, we make a systematic analysis of the optical reach for these three connectivity schemes in a four band system and we identify the resulting performance trade-offs.

System under investigation

We consider a Core network with an average inter-node distance of 150 km consisting of three spans of 50 km in length, as shown in Fig.1. To compensate for the losses, Doped Fiber Amplifiers (DFA) are employed[5] while a BDFA[6] is considered for the E-band. For all amplifiers, the presence of GFFs with a sole purpose of offering an effectively flat gain with <1dB ripple across the band is mandatory. The optical nodes are WSS-based to allow for the power equalisation of channels between ingress/egress links. These technologies are not commercially available today but they are mature. The band

Table 1: Amplification details used in our study

	Used Range (nm)	Noise Figure (dB)	Amplifier Type
E band	1410-1425	6.0	BDFA
S_1 band	1455-1480	5.5	TDFA
S_2 band	1485-1510	5.5	TDFA
C band	1530-1565	5.5	EDFA
L band	1570-1615	6.0	EDFA

Table 2: Operational parameters used in our study

	Modulation Format	Baud Rate (Gbaud)	Ch.Sp. (GHz)	Data Rate (Gb/s)	OSNIR @ BER 10^{-3} (dB)
100G	PM-QPSK	32	37.5	100	9.80
200G	PM-QPSK	64	75	200	9.80
	PM-8QAM	48	50	200	13.70
	PM-16QAM	32	37.5	200	16.55
400G	PM-QPSK	128	137.5	400	9.80
	PM-8QAM	96	100	400	13.70
	PM-16QAM	64	75	400	16.55
	PM-32QAM	48	50	400	19.50
800G	PM-16QAM	128	137.5	800	16.55
	PM-32QAM	96	100	800	19.50

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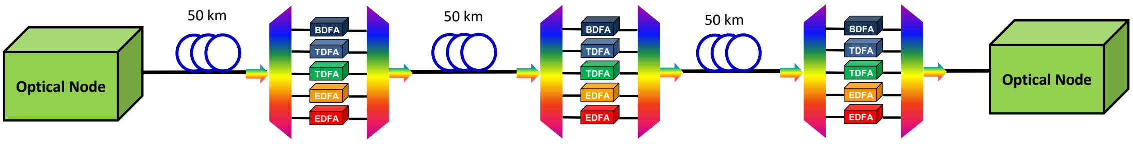

Fig. 1: The transmission link used to interconnect two consecutive nodes

details and the corresponding DFAs are shown in Table 1. Other system operational parameters are listed in Table 2.

We have considered the most commercially relevant symbol rates (32 to 128Gbaud[7]) and polarisation multiplexed (PM) modulation formats to study 100G, 200G, 400G and 800G systems in this work, as shown in Table 2.

Proposed power allocation algorithm

An OMB system, is degraded by amplified spontaneous emission (ASE) noise, four wave mixing (FWM) and SRS[1],[2],[4],[5],[8]. ASE noise and FWM are intra-band effects, while SRS is an inter-band effect. The OSNIR accounts for all three effects as follows:

$$OSNIR = \frac{P_{ch} \cdot \prod_{i=1}^{N_s} G_{SRS,i}}{P_{ASE} + P_{FWM}} \qquad (1)$$

where N_s equals to the number of fiber spans a channel is traversing; P_{ch} denotes the power at link ingress for the channel under observation, $G_{SRS,i}$ calculates the SRS Gain/Loss effect for the i^{th} fibre span as in[1],[5], P_{FWM} is the power of FWM interference as in[1],[5],[9] and P_{ASE} is given by

$$P_{ASE} = \sum_{i=1}^{N_s} \left[hf \left(NF_i \cdot G_i - 1 \right) B_0 \prod_{r=i+1}^{N_s} G_{SRS,r} \right] \qquad (2)$$

In (1), we ignore the cross-coupling between SRS and FWM, since the resulting power allocation scheme leads to total launch powers lower than +21 dBm, a constraint which makes the SRS-FWM interplay a secondary effect based on[4]. In addition, the impact of SRS between successive fibre links is mitigated by means of a WSS-based node as in[1],[5].

To optimize the physical layer performance simultaneously across the *E, S, C* and *L* bands, we introduce the merit function:

$$F'\left(P_1, P_2, \ldots, P_{N_{ch,\mathrm{tot}}}\right) = \sum_{b=1}^{N_{ch,\mathrm{tot}}} \alpha_b \left(\frac{1}{OSNIR_b\left(\ldots, P_{b-1}, P_b, P_{b+1}, \ldots\right)} \right)^2 \qquad (3)$$

where α_b are suitably chosen weights and $N_{ch,total}$ denotes the total number of channels across all bands that contribute to the OSNIR degradation of (1) due to SRS with a 15 THz bandwidth[1].

In (3), the bands and their OSNIR are entangled and the scope of the optimization (3) is to find the α_b and the power of the central channel in each band, P_E, P_{s1}, P_{s2}, P_C, P_L that minimizes (3), following the high-level objectives set by the designer. Moreover, the condition $P_{tot,SRS} < +21$ dBm[4] is set, in order to make sure that SRS is a second order effect. $P_{min} < P_E, P_{s1}, P_{s2}, P_C, P_L < P_{max}$ were set to avoid a catastrophic OSNIR degradation due the small channel power calculated by (3), while P_{max} is set, e.g. +1 dBm, to avoid a DFA operation in its saturation regime.

Eq.(3) generalizes the merit function in[5], as it a) allows to balance the OSNIR performance for any channel of an OMB system, not only for the central one in each band and b) through the weights α_b, elaborate OSNIR designs are feasible. In this work, we consider three OSNIR performance targets using the values of Table 3: (i) a direct extension of[5] to incorporate the E-band; (ii) an OSNIR with < 1 dB performance variance across the entire spectrum; (iii) a split of the entire spectrum in two zones {E, S_1} and {S_2, *C, L*} and request an OSNIR with < 1 dB performance variance within each zone.

Table 3: Physical fibre parameters used in OSNIR estimations

	E	S_1	S_2	C	L
λ (nm)	1417.5	1467.5	1497.5	1547.5	1592.5
a (dB/km)	0.28	0.246	0.23	0.211	0.209
D (ps/nm/km)	8.63	12.05	13.96	16.93	19.42

Results

To derive the optimal launch powers of the three configurations, the following methodology was followed: (i), the weights {α_b} in (3) were all set to 1 as in[5]; (ii) optimization was performed, returning the weight values $\alpha_b=\{12, 1, 1, 0.4, 0.5\}$ for $b=\{E, S_1, S_2, C, L\}$; (iii) a similar arrangement was made for the schemes with the two zones, {E, S_1} and {S_2, C, L}. The results of the optimisation are shown in Fig.2 for a fully loaded system and a baud rate of 32 Gbaud. In particular, Fig.2a shows the attainable OSNIR performance per band and Fig.2b shows the corresponding launch powers. It is evident in Fig.2b that the E-band is already in the NL-limited regime. Therefore, the guard-band in the E-band is twice as wide as in other bands. In the arrangement (i) the maximum difference between

		100G	200G			400G				800G	
		PM-QPSK 32 Gbaud	PM-QPSK 64 Gbaud	PM-8QAM 48 Gbaud	PM-16QAM 32 Gbaud	PM-QPSK 128 Gbaud	PM-8QAM 96 Gbaud	PM-16QAM 64 Gbaud	PM-32QAM 48 Gbaud	PM-16QAM 128 Gbaud	PM-32QAM 96 Gbaud
(a)	E band	1950 km	1800 km	750 km	450 km	1800 km	750 km	300 km	150 km	300 km	150 km
	S_1 band	2250 km	2250 km	1350 km	750 km	2250 km	1350 km	600 km	300 km	600 km	300 km
	S_2 band	2250 km	2250 km	1500 km	750 km	2250 km	1500 km	750 km	300 km	750 km	300 km
	C band	2250 km	2250 km	1950 km	1050 km	2250 km	1950 km	900 km	450 km	900 km	450 km
	L band	2250 km	2250 km	1650 km	750 km	2250 km	1650 km	750 km	300 km	750 km	300 km
(b)	E band	2250 km	2250 km	1050 km	600 km	2250 km	1050 km	600 km	150 km	450 km	150 km
	S_1 band	2250 km	2250 km	1050 km	600 km	2250 km	1050 km	600 km	150 km	450 km	150 km
	S_2 band	2250 km	2250 km	1050 km	600 km	2250 km	1050 km	600 km	150 km	450 km	150 km
	C band	2250 km	2250 km	1050 km	600 km	2250 km	1050 km	600 km	150 km	450 km	150 km
	L band	2250 km	2250 km	1050 km	600 km	2250 km	1050 km	600 km	150 km	450 km	150 km
(c)	E band	1650 km	1650 km	600 km	300 km	1650 km	600 km	300 km	150 km	300 km	150 km
	S_1 band	1650 km	1650 km	600 km	300 km	1650 km	600 km	300 km	150 km	300 km	150 km
	S_2 band	2250 km	2250 km	1950 km	1050 km	2250 km	1950 km	1050 km	450 km	1050 km	450 km
	C band	2250 km	2250 km	1950 km	1050 km	2250 km	1950 km	1050 km	450 km	1050 km	450 km
	L band	2250 km	2250 km	1950 km	1050 km	2250 km	1950 km	1050 km	450 km	1050 km	450 km

0 - 300 km | 300 - 600 km | 600 - 900 km | 900 - 1200 km | 1200 - 1500 km | 1500 - 1800 km | 1800 - 2100 km | 2100 - 2250 km

Fig. 3: Attainable reach for three optimization methods to: (a) balanced OSNIR between different bands, (b) flat OSNIR between all bands, (c) flat OSNIR within two zones.

the OSNIR values is 4 dB. The lower OSNIR of E-band computed with (i) and (iii) compared with (ii), is attributed to the higher power of S and C bands, which results in a stronger SRS, due to the higher overall power, and as a consequence

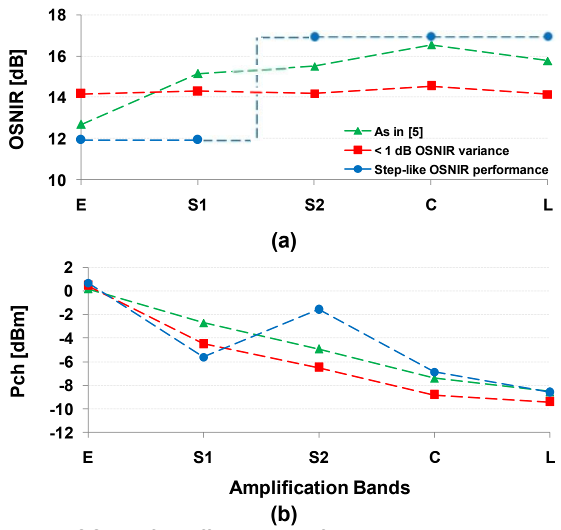

Fig. 2: OSNIR for different amplification bands using three different power allocation schemes

to a greater E-band depletion.

Based on the same methodology, optimal launch powers were deduced for different symbol-rates for 100G to 800G line-rates. The attainable transparent lengths are summarized in Fig.3 where colours have been used to facilitate visualization.

The following conclusions are drawn: first, method (i) maximizes the transparent length for some bands but the transparent lengths between different bands may vary widely making the network operation more complex. This 'patchy' OSNIR performance may lead to considerable wavelength blocking in WRNs. Second, following method (ii), the optical reach is the same across all bands albeit of a shorter length compared to (i). In this way, network connectivity is greatly enhanced, as an operator will be able to resort to larger number of channels of equal performance to interconnect any pair of nodes. Third, following method (iii), the transparent length of channels in E, S_1 bands can be exploited for shorter distances, while the channels in S_2, C, L bands can be assigned to interconnect more distant nodes. The reach of the channels in the second zone is almost tripled compared to those in the first zone for all modulation formats and symbol-rates. Moreover, this scheme leads to the highest OSNIR in S_2, C and L bands compared with the other two schemes.

Finally, it is made evident that the most critical technological parameter that determines or not the widespread deployment of higher line-rates in a national network is the attainable symbol-rate. There is a strong need to increase the symbol-rate beyond 128 Gbaud, if an operator desires to interconnect nodes with > 400G in the context of WRN and not only between routers in tandem.

Conclusions

To assess the potential of three connectivity schemes employing the E, S, C and L bands, we have developed a rigorous OSNIR optimisation method. Via the subsequent optimal launch powers per band, the optical reach and the corresponding performance trade-offs for these schemes were deduced revealing that a uniform OSNIR performance maximizes the number of available channels, albeit a slightly reduced reach.

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