Regeneration Savings in Coherent Optical Networks with a New Load-dependent Reach Maximization

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Abstract We propose a new load-dependent reach maximization procedure in dispersion-uncompensated optical networks with coherent detection, and estimate the electro-optic regeneration savings with respect to the standard full-load reach approach.

Introduction

We consider here the physical layer design of flexible optical networks, where dispersion-uncompensated (DU) wavelength division multiplexed (WDM) dual-polarization (DP) optical digital signals are transmitted and coherently detected. From the source, the destination may be transparently reached via a single lightpath without electro-optic regeneration (EOR), or through a concatenation of lightpaths on possibly different wavelengths, with EOR from one lightpath to the next one. To minimize the number of costly EORs, the quality-of-transmission aware routing and wavelength assignment (RWA) algorithm first tries to set-up a circuit along a single lightpath. Connection may be unfeasible for two reasons: i) unavailability of the same wavelength across successive fibers along the lightpath, leading to wavelength blocking (WB); ii) the received signal to noise ratio (SNR) for the considered modulation format is below a required minimum $S_0$, leading to SNR blocking (SB).

We concentrate here on SB due to accumulation of linear and nonlinear optical impairments. The standard approach is to set-up only lightpaths whose physical length is below the full-load (FL) reach$^1$, i.e., the maximum length guaranteeing a received SNR above $S_0$ when all W wavelengths on all fibers are occupied. The FL reach is used regardless of the actual wavelength load $u$, i.e., the fraction of network wavelengths actually utilized by set-up lightpaths. Using the FL reach is clearly conservative, since wavelengths saturation at the network core prevents the average network load $u$ to reach unity. In this paper, we propose a new power selection strategy that maximizes the reach at the actual load $u$, and quantify the potential EOR savings with respect to using the FL reach and the power selection strategy in$^1$.

Nonlinear transmission with ON/OFF traffic

Focus on a reference lightpath from source to destination, composed of $H$ hops across access nodes, where the $k$-th hop is a concatenation of $S_k$ amplified spans followed by the crossing of the $k$-th intermediate node, for $k = 1, \ldots, H$. A span consists of a transmission fiber followed by a lumped optical amplifier. A node is composed of a wavelength demultiplexer, add/drop block and output multiplexer. The lightpath is composed of $N_s = \sum_{k=1}^{H} S_k$ spans. Interfering traffic is modeled by assuming that each of the $W-1$ remaining wavelengths of the $k$-th hop independently carries a lightpath (hence power) with known probability $u_k$, $k = 1, \ldots, H$. Within a first-order regular perturbation analysis, the received SNR over the bandwidth of the DP signal of interest after propagation across the reference lightpath is$^2$:

$$SNR(P, N_s, u) = \frac{P}{N_A + a_{NL}(N_s, u)P^3}$$

where $P$ is the DP reference power level at the input of each transmission fiber section; $N_A$ is the amplified spontaneous emission power which scales linearly with $N_s$; $a_{NL} = a_{NL}^SC + a_{NL}^SCI$, is the nonlinear interference (NLI) coefficient$^2$ contributed by single- and cross-channel interference (SCI, XCI). While $a_{NL}^SCI$ is deterministic, we can prove$^3$ that in DU links $a_{NL}^SCI \cong \sum_{\nu \neq 0} C_p \sum_{k=1}^{H} S_k I_{pk}$, where $C_p$ is a link- and pump-dependent coefficient at wavelength $\lambda_p$, and the indicator random variable (RV) $I_{pk}$ equals 1 (with probability $u_k$) if a lightpath is ON at $\lambda_p$ at hop $k$, and 0 otherwise, as sketched in Fig. 1. Hence the $a_{NL}$ coefficient and in turn the received SNR are RVs, whose statistics depend on the load vector $u = [u_1, \ldots, u_H]$. The digital signal has a forward error-correction code whose SNR threshold (plus margin) for the signal modu-
P dBm
−15
−10
10

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width), although the theory is developed for non-
varying formats with or without EOR (i.e., the maximum

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visualize both the maximum number of spans that

are bridged without EOR (i.e., the maximum

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load-dependent reach) and the associated opti-
mization format is \(S_0\). We declare an SB event when

\(SNR < S_0\).

The design of point-to-point DU transmission

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systems for DP WDM coherent systems is based on

the received SNR contours versus number of spans \(N_s\) and transmitted power \(P\) (assumed

here the same for all signals). In a networking

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scenario, however, the SNR is a RV. We

propose here to base the design of DU net-

works on contours of the SB probability \(P_{SB} \triangleq \Pr\{SNR(P, N_s, u) < S_0\}\) at fixed load \(u\) versus

both power per channel \(P\) and number of spans \(N_s\).

The proposed load-dependent RWA, which

needs only knowledge of the load vector \(u\), de-

clares that a new lightpath of length \(N_s\) has suf-

ficient SNR at destination if \(P_{SB}\) is less than or

equal to a target level \(P_{SB}\) for the selected mod-

ulation format. All details of the SB probability

derivation from the statistics of the modulation-

format-independent \(a_{NL}\) from the Gaussian Noise

(GN) model \(^2\) are presented in \(^3\).

Results

From the \(P_{SB}\) contours at the target level we vi-

ualize both the maximum number of spans that

can be bridged without EOR (i.e., the maximum

load-dependent reach) and the associated opti-
mal power. In the numerical calculations we

assumed the spans are identical, the load \(u_k\) and

the spans per hop \(S_k\) are uniform at all hops \(k = 1, \ldots, H\), with \(S = 2\) spans per hop, and all sig-
nals have the same format (i.e., power and band-

width), although the theory is developed for non-

uniform \(u_k\), \(S_k\) \(^3\) and can be extended to mixed

modulation formats. Fig. 2 shows the SB prob-

ability contours at a target electrical SNR \(S_0 =

9.8 dB (over the matched-filter bandwidth, yield-
ing a \(10^{-3}\) bit error rate (BER) for DP quadrature

phase shift keying (DP-QPSK)), for \(W = 81\) wave-
lengths and \(R = 10\) Gbaud signals transmitted

with spacing \(\Delta f = 12.5\) GHz (bandwidth efficien-
cy \(\eta = \frac{R}{\Delta f} = 0.8\) over \(N_s\) 100 km DU spans

dispersions \(\Delta D = 2\) ps/nm/km, attenuation \(\alpha = 0.2\) dB/km,

nonlinear coefficient \(\gamma = 1.3 W^{-1} k m^{-1}\) and

amplifiers noise figure \(F = 4\) dB. The points of

maximum reach at the optimal power are marked

by red circles in the figure. We indicate their coor-

dinates as \([N_0(u), P_0(u)]\). At \(u = 1\) and \(u = 0\)

the SB contours at all \(P_{SB}\) levels coincide. For

all \((P, N_s)\) pairs inside the region delimited by

the red contour (at \(u = 1\)) or blue contour (at

\(u = 0\)) the SB probability is zero, while out-

side it is 1. Instead, at any intermediate load

\(0 < u < 1\) the contours vary with the value of

\(P_{SB}\), and all \((P, N_s)\) pairs inside each contour

yield \(Pr\{SNR(P, N_s, u) < S_0\} \leq P_{SB}\). For in-

stance, at loads \(u = 0.6\) and \(u = 0.1\) the green

lines show the contours at level \(P_{SB} = 10^{-3}\).

The locus of maximum reach points, as \(u\) varies,

can be shown to lay on the dashed-dotted straight

diagram shown in Fig. 2 parallel to the (lower)

linear asymptote and shifted by \(10\log(3/2) \approx 1.76\) dB

above that.

In Fig. 2 the linear asymptote and hence

the dashed-dotted line have slope 1dB/decade,

hence the magenta arrows in the figure indicate

1.76 dB on each axis direction. This has a funda-

mental consequence, first noted in \(^1\). If we fix

\(P\) to the full load optimal value \(P_0(1)\) (magenta
dotted line) then the ratio between the FL reach

\(N_0(1)\) and the reach at any other load \(u < 1\) is always

smaller than 2/3. Thus, if in the RWA algorithm

we use the FL reach \(N_0(1)\), at most we under-

estimate the true reach by a factor 1/3, i.e., by

33\%. This was the rationale for proposing the FL

RWA design that uses the distance-independent

power \(P_0(1)\) in \(^1\). However, suppose for instance

the actual load is only \(u = 0.1\). If we use the

true maximum reach power \(P \equiv P_0(u) = -6\) dBm

(see contour at \(u = 0.1\)) we find that the max-

imum reach is \(N_0(u) = 37\) spans, which com-

pared with the FL reach \(N_0(1) = 23\) spans gives

a reach under-estimation by the FL RWA with re-
spect to the proposed load-dependent RWA by:

\(H \triangleq \frac{N_0(u) - N_0(1)}{N_0(1)} = 37.8\%\), which is above

33%. This means that if we know the average

wavelength load \(u\) and then select the maximum-

reach power \(P_0(1)\), the under-estimation with re-
spect to the actual reach \(N_0(u)\) when adopting

the FL RWA can be larger than 33%. The optimal

power \(P_0(1)\) and the corresponding reach \(N_0(1)\)
can be analytically derived at any load $u$\(^3\). The reach under-estimation $U$ turns out to be a decreasing function of dispersion $D$, symbol rate $R$, and load $u$. Fig. 3 shows $U$ versus load $u$ for DP-QPSK at both $R = 10$Gbaud and $R = 28$Gbaud on standard single-mode fiber (SMF, $D = 17$ ps/nm/km), both with and without ideal digital-backpropagation (DBP). With ideal DBP only XCI is left ($a_{NL} = 0$) and the reach $N_0$ is independent of channel symbol rate and just depends on bandwidth efficiency $\eta$. $U$ is below $\approx 20\%$ in all practical cases on SMF links at loads above 0.4.

We next need to quantify the savings in EOR when using the load-dependent RWA. A quick estimation is obtained as follows. We get the distribution of the lightpath length $N_s$ (spans) in the network from simulations when SNR blocking is neglected. Each circuit is set up on a single span (hop) of the network from simulations up to first WB; average load $u$ is 0.46. Let the topology-dependent simulated normalized histogram of lightpath lengths $N_s$ be \(P(N_s, u)\). We can thus estimate the expected number of required EOR when the reach is $N_0$ as $E[\text{EOR}|N_0] = \sum_{N_s} N_s P(N_s, u) \left( \frac{N_s}{N_0} - 1 \right)$, where $N_{\text{max}}$ is the maximal $N_s$ in the network, and \([x]\) is the ceiling function. The percent savings $R(u)$ in EOR operations using our load-dependent RWA with respect to the full-load RWA is:

$$R(u) = \frac{E[\text{EOR}|N_0(u)] - E[\text{EOR}|N_0(u)]}{E[\text{EOR}|N_0(u)]} \cdot 100.$$  

Note that whenever $N_0(1) < N_{\text{max}} < N_0(u)$ the savings are 100%, since no regenerations are required with the load-dependent RWA. Fig. 4 shows EOR savings $R$ (red) and under-estimation $U$ (blue) versus target SNR $S_0$ (i.e., modulation format) at the first-WB load $u = 0.46$ in a 46-node US network\(^4\) in uniform traffic, at $R = 28$Gbaud on SMF fiber, both with (solid) and without (dashed) ideal DBP. We note that at the smallest $S_0$ of 6.8 dB (corresponding to DP binary phase shift keying at BER = \(10^{-3}\)) no regenerations are needed in the US network even using $N_0(1)$, hence $R$ is undefined. As we increase $S_0$ we go to a situation where $N_0(1) < N_{\text{max}} < N_0(u)$, yielding 100% savings. As the modulation levels increase the required $S_0$ increases (e.g., $S_0 = 15.8$dB for DP 16 quadrature-amplitude modulation), hence $N_0$ decreases, and the %EOR savings $R$ decrease towards the values of under-estimation $U$. Thus under-estimation is also a reasonable indicator of %EOR savings only for higher-order modulation formats.

**Figures**

Fig. 3: Reach under-estimation $U$ of FL RWA\(^1\) with respect to proposed load-dependent RWA versus load $u$ in a DU SMF link ($D = 17$ ps/nm/km) with $W = 81$ WDM DP-QPSK ($S_0 = 9.8$dB), at SNR blocking probability $P_{SB} = 10^{-3}$, with 100km/span, $S = 2$span/hop, $\eta = \frac{R}{57} = 0.8$, $F = 4$dB.

Fig. 4: EOR savings $R$ (red) and under-estimation $U$ (blue) versus target SNR $S_0$ (i.e., modulation format) at the first-WB in the US network\(^4\), at $R = 28$Gbaud on SMF fiber. Other data as in Fig. 2. Solid: ideal DBP. Dashed: no DBP. $R$ and $U$ averaged over 100 simulations up to first WB; average load $u = 0.46$.

**Conclusions**

We have analyzed the potential EOR savings when using a load-dependent reach in place of the standard full-load reach\(^1\). For a 46-node US network in uniform traffic over SMF links we find a reduction from 40% (no DBP) to 60% (ideal DBP) EOR operations at the load of first wavelength blocking ($u = 0.46$) for a DP-QPSK format. Higher-order modulations show smaller savings.

**References**