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 regenerations 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

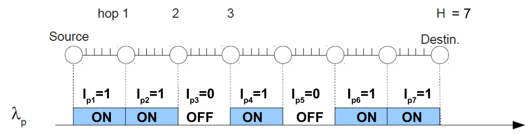

Fig. 1: ON-OFF lightpath process on p-th wavelength.

$\mathcal{S}_k$ amplified spans followed by the crossing of the k-th intermediate node, for $k = 1, ..., H$. 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 $N_s = \sum_{k=1}^{H} \mathcal{S}_k$ 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]:

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

where P is the DP reference lightpath power at the input of each transmission fiber section; N_A is the amplified spontaneous emission power which scales linearly with N_s; $a_{NL} = a_{NL}^{SCI} + a_{NL}^{XCI}$ 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 $a_{NL}^{XCI} \cong \sum_{p\neq 0} \mathcal{C}_p \sum_{k=1}^{H} \mathcal{S}_k I_{pk}$, where $\mathcal{C}_p$ is a link- and pump-dependent coefficient at wavelength λ_p, and the indicator random variable (RV) I_{pk} equals 1 (with probability u_k) if a lightpath is ON at λ_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 $\mathbf{u} = [u_1, ..., u_H]$. The digital signal has a forward error-correction code whose SNR threshold (plus margin) for the signal modu-

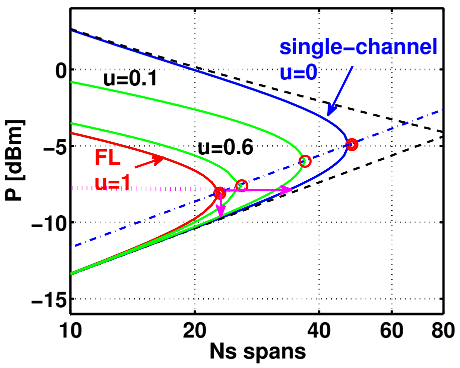

Fig. 2: Contours of SNR-blocking probability at level $\mathcal{P}_{SB} = 10^{-3}$ versus power P and number of spans N_s at load values $u = [0, 0.1, 0.6, 1]$. All pairs (P, N_s) inside each contour yield $\Pr\{SNR(P, N_s, \mathbf{u}) < S_0\} \le \mathcal{P}_{SB}$, with SNR over signal bandwidth $S_0 = 9.8$dB (DP-QPSK at BER=10^{-3}).

lation format is S_0. We declare an SB event when $SNR < S_0$.

The design of point-to-point DU transmission 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 scenario, however, the SNR is a RV. We propose here to base the design of DU networks on contours of the SB probability $P_{SB} \triangleq \Pr\{SNR(P, N_s, \mathbf{u}) < S_0\}$ at fixed load $\mathbf{u}$ 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 $\mathbf{u}$, declares that a new lightpath of length N_s has sufficient SNR at destination if P_{SB} is less than or equal to a target level $\mathcal{P}_{SB}$ for the selected modulation format. All details of the SB probability derivation from the statistics of the modulation-format-indepenent a_{NL} from the Gaussian Noise (GN) model[2] are presented in[3].

Results

From the P_{SB} contours at the target level we visualize both the maximum number of spans that can be bridged without EOR (i.e., the maximum load-dependent reach) and the associated optimal power. In the numerical calculations we assumed the spans are identical, the load u_k and the spans per hop $\mathcal{S}_k$ are uniform at all hops $k = 1, \ldots, H$, with $\mathcal{S} = 2$ spans per hop, and all signals have the same format (i.e., power and bandwidth), although the theory is developed for non-uniform u_k, $\mathcal{S}_k$[3] and can be extended to mixed modulation formats. Fig. 2 shows the SB probability contours at a target electrical SNR $S_0 = 9.8$dB (over the matched-filter bandwidth, yielding a 10^{-3} bit error rate (BER) for DP quadrature phase shift keying (DP-QPSK)), for $W = 81$ wavelengths and $R = 10$Gbaud signals transmitted with spacing $\Delta f = 12.5$GHz (bandwidth efficiency $\eta = \frac{R}{\Delta f} = 0.8$) over N_s 100km DU spans (dispersion $D = 2$ps/nm/km, attenuation $\alpha = 0.2$dB/km, nonlinear coefficient $\gamma = 1.3$W^{-1}km^{-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 coordinates as $[N_0(u), P_0(u)]$. At $u = 1$ and $u = 0$ the SB contours at all $\mathcal{P}_{SB}$ 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 outside it is 1. Instead, at any intermediate load $0 < u < 1$ the contours vary with the value of $\mathcal{P}_{SB}$, and all (P, N_s) pairs inside each contour yield $\Pr\{SNR(P, N_s, \mathbf{u}) < S_0\} \le \mathcal{P}_{SB}$. For instance, at loads $u = 0.6$ and $u = 0.1$ the green lines show the contours at level $\mathcal{P}_{SB} = 10^{-3}$. The locus of maximum reach points, as u varies, can be shown to lay on the dashed-dotted straight line shown in Fig. 2 parallel to the (lower) linear asymptote and shifted by $10\text{Log}(3/2) \cong 1.76$ 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 *fundamental 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%[1]. 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 maximum reach is $N_0(u)$ =37 spans, which compared with the FL reach $N_0(1)$ =23 spans gives a reach under-estimation by the FL RWA with respect to the proposed load-dependent RWA by: $\mathcal{U} \triangleq \frac{N_0(u) - N_0(1)}{N_0(u)} 100 = 37.8\%$, which is above 33%. This means that if we know the average wavelength load u and then select the maximum-reach power $P_0(u)$, the under-estimation with respect to the actual reach $N_0(u)$ when adopting the FL RWA can be larger than 33%. The optimal power $P_0(u)$ and the corresponding reach $N_0(u)$

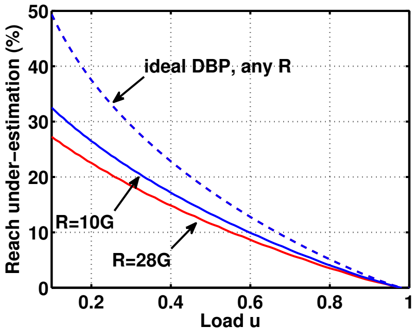

Fig. 3: Reach under-estimation $\mathcal{U}$ of FL RWA[1] with respect to proposed load-dependent RWA versus load u in a DU SMF link ($D = 17$ps/nm/km) with $W = 81$ WDM DP-QPSK ($S_0 = 9.8$dB), at SNR blocking probability $\mathcal{P}_{SB} = 10^{-3}$, with 100km/span, $\mathcal{S} = 2$span/hop, $\eta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

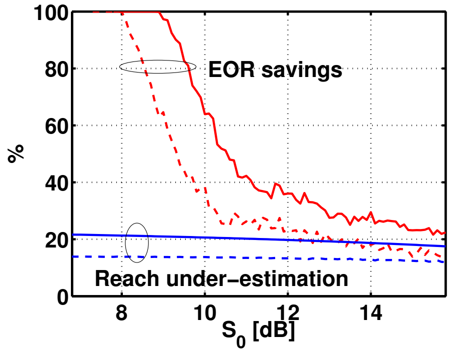

Fig. 4: EOR savings $\mathcal{R}$ (red) and under-estimation $\mathcal{U}$ (blue) versus target SNR S_0 (i.e., modulation format) at the first-WB in the US network[4], at $R = 28$Gbaud on SMF fiber. Other data as in Fig. 2. Solid: ideal DBP. Dashed: no DBP. $\mathcal{R}$ and $\mathcal{U}$ averaged over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

can be analytically derived at any load u[3]. The reach under-estimation $\mathcal{U}$ turns out to be a decreasing function of dispersion D, symbol rate R, and load u. Fig. 3 shows $\mathcal{U}$ 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 without and with ideal digital-backpropagation (DBP). With ideal DBP only XCI is left ($a_{NL} = a_{NL}^{XCI}$) and the reach N_0 is independent of channel symbol rate and just depends on bandwidth efficiency η . $\mathcal{U}$ is below $\cong 20\%$ 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 lightpath until the first WB, when the measured load is u. Let the topology-dependent simulated normalized histogram of lightpath lengths N_s be $\mathcal{P}(N_s, u)$. We can thus estimate the expected number of required EOR when the reach is N_0 as $E[\text{EOR}|N_0] = \sum_{N_s=1}^{N_{max}} \mathcal{P}(N_s, u)(\left\lceil \frac{N_s}{N_0} \right\rceil - 1)$, where N_{max} is the maximal N_s in the network, and $\lceil x \rceil$ is the ceiling function. The *percent savings* $\mathcal{R}(u)$ in EOR operations using our load-dependent RWA with respect to the full-load RWA is:

$$\mathcal{R}(u) = \frac{E[\text{EOR}|N_0(1)] - E[\text{EOR}|N_0(u)]}{E[\text{EOR}|N_0(1)]} \cdot 100.$$

Note that whenever $N_0(1) < N_{max} < N_0(u)$ the savings are 100%, since no regenerations are required with the load-dependent RWA. Fig. 4 shows EOR savings $\mathcal{R}$ (red) and under-estimation $\mathcal{U}$ (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 $\mathcal{R}$ is undefined. As we increase S_0 we go to a situation where $N_0(1) < N_{max} < N_0(u)$, 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 $\mathcal{R}$ decrease towards the values of under-estimation $\mathcal{U}$. Thus under-estimation is also a reasonable indicator of %EOR savings only for higher-order modulation formats.

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

1 P. Poggiolini et al., “The LOGON Strategy for Low-Complexity Control Plane Implementation in New-Generation Flexible Networks” Proc. *OFC’13*, paper OW1H.3.

2 P. Poggiolini, “The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems,” *J. Lightw. Technol.* **30**, 3857 (2012).

3 A. Bononi et al., “Load-aware Transparent Reach Maximization in Flexible Optical Networks,” Proc. *NOC’14*, Milan, (2014).

4 A. Morea et al. “QoT function and A* routing: an optimized combination for connection search in translucent networks,”, *J. Opt. Netw.* **7**, 42 (2008).