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Regeneration savings in flexible optical networks with a new load-aware reach maximization ☆

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ABSTRACT

We propose and analyze a new load-aware reach maximization procedure based on the Gaussian Noise model for dispersion-uncompensated optical networks with coherent detection. We estimate the opto-electronic regeneration savings with respect to the standard full-load reach approach, and find examples where significant savings can be achieved. The load aware reach and its corresponding optimal power can be computed in real time by the routing and wavelength assignment unit to make statistical decisions about setting-up new lightpaths or regenerating existing ones.

1. Introduction

This paper addresses the physical layer design of flexible optical networks [1–8] and its interplay with the routing layer. In such circuit-switched dispersion uncompensated (DU) fiber-optic networks, wavelength division multiplexed (WDM) dual polarization (DP) optical digital signals are transmitted and coherently detected. Each fiber carries at most W wavelengths with possibly mixed modulation formats. From the source, the destination may be transparently reached via a single lightpath at a specific wavelength without opto-electronic regeneration (OER), or through a concatenation of lightpaths on possibly different wavelengths, with OER from one lightpath to the next one. To minimize the number of costly OERs, the quality-of-transmission (QoT) aware routing and wavelength assignment (RWA) unit first tries to set-up a circuit along a single lightpath. A 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).

In this paper, which is an extension of [9], we concentrate on the SB due to accumulation of linear and nonlinear optical impairments [1,6,3,7,8]. The standard approach is to set-up only lightpaths whose physical length is below the *full-load (FL) reach*, 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 as a lightpath-length threshold above which intermediate regenerations are introduced, regardless of the actual wavelength load, i.e., the fraction of wavelengths actually utilized along the current lightpath. Using the FL reach is clearly conservative, since wavelengths saturation at the network core prevents the wavelength load to reach unity. In this paper, we propose a new power selection and OER regeneration strategy where the reach is maximized at the actual wavelength load, and quantify the potential OER savings with respect to using the FL reach and the power selection strategy suggested in [6]. The analysis in the present paper is based on the Gaussian Noise (GN) model for DU coherent links [10,6–8].

☆ Invited paper.

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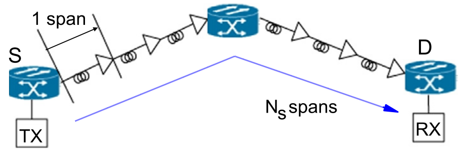

Fig. 1. Sketch of selected reference lightpath from source S to destination D across N_s spans. $H=2$ hops and $\mathcal{S}=3$ span/hop in the example.

The paper is organized as follows. Section 2 briefly recalls the expression of the received electrical SNR that includes nonlinearity according to the GN model, and defines the SB events. Section 3 introduces the key ideas of the new load-aware reach maximization procedure and anticipates the main numerical results of this paper. Section 4 then provides the full analytical details behind the numerical results. Conclusions are finally drawn in Section 5.

2. Nonlinear transmission model

We focus on the transparent transmission of a DP signal across a *reference* lightpath from source to destination, as depicted in Fig. 1. A lightpath is a sequence of H *hops* across access nodes (i.e., add-drop nodes where circuits may originate and terminate), where the hop k is a concatenation of $\mathcal{S}_k$ amplified spans followed by the crossing of the k-th intermediate node, for $k=1,\ldots,H$. A *span* is composed of a transmission fiber followed by an end-line lumped optical amplifier. A *node* is composed of a wavelength demultiplexer, an add/drop block, a possible switching block, and an output multiplexer.[1] In our calculations, the losses in crossing a node are assumed to be equivalent to those in crossing one span.

The reference lightpath is composed of $N_s=\sum_{k=1}^{H}\mathcal{S}_k$ spans. We assume that each of the $W-1$ remaining wavelengths of hop k carries an interferer lightpath (hence carries power) with known probability u_k, $k=1,\ldots,H$. Such wavelength utilization probabilities (or *loads*) can be estimated from network traffic, and we collect them in the (*wavelength*) load vector $\underline{u}=[u_1,\ldots,u_H]$.

Within a first-order perturbation analysis, the received SNR over the bandwidth of the DP signal of interest after propagation across the reference lightpath can be expressed as [13,14]

$$SNR(P,N_s,\underline{u})=\frac{P}{\beta(N_s+H)+a_{NL}(N_s,\underline{u})P^3} \quad (1)$$

where P is the DP reference signal power at the input of each transmission fiber section; $N_A\triangleq\beta(N_s+H)$ is the amplified spontaneous emission (ASE) power from the (N_s+H) optical amplifiers, with $\beta\triangleq h\nu FGB_r$, where h is Planck's constant, ν is the optical carrier frequency, F is the amplifier noise figure, G is the amplifier gain (equal to the span loss) and B_{rx} is the receiver equivalent noise bandwidth; a_{NL} is the nonlinear interference (NLI) coefficient [13,10] which depends on the number of spans and on the load vector $\underline{u}$, which in turn depends on the offered traffic and on the RWA algorithm. Since the number of interfering wavelengths is a random variable (RV), then also the a_{NL} coefficient and the received SNR are RVs, whose statistics depend on $\underline{u}$. SNR is deterministic only in the two limiting cases $\underline{u}=\underline{0}$ (no interfering wavelengths along our lightpath , i.e., single channel propagation) and $\underline{u}=\underline{1}$ (full load operation) where there is no random variability of the number of interfering lightpaths.

We assume the digital signal is coded with a forward error-correction (FEC) code whose SNR threshold (plus margin) for the signal modulation format is S_0. We declare an SB event when $SNR(P,N_s,\underline{u})<S_0$. The circuit is in that case routed via multiple lightpaths and requires OER at intermediate nodes. In this work we do not consider a possible change of modulation format and/or FEC, in response to an SB event.

[1] Note that add/drop and switching are commonly performed at the same location. However, a hop in our treatment logically corresponds to a segment between add/drop nodes.

3. Summary of results

We anticipate in this section our main results regarding both the load-aware reach and the OER savings. Numerical results are provided for the simplified case of: (i) identical spans across the network; (ii) WDM signals with same spectrum, thus power and bandwidth; (iii) ON/OFF independent traffic on all $W-1$ interfering wavelengths at each hop along the reference lightpath; and (iv) uniform load at all hops, i.e., $u_k\equiv u$ for all $k=1$,..., H.

It should be clear that such assumptions are highly simplistic, and are justified only in view of a first coarse analysis of the possible gains of the proposed method. Extensions of the theory to hop-dependent loads, still assuming independent per-wavelength traffic, are presented in Section 4. In actual network operation, however, there will be clear dependencies between wavelengths used on one link and on the next link. There are also dependencies between wavelengths used on the same link, especially when impairment-aware RWA algorithms are used to allocate lightpaths. The theory of such correlations is partly tackled in the more advanced Markovian traffic model analyzed in Appendix B.

3.1. SNR blocking probability contours

The key ideas of our proposed load-aware regeneration strategy are best understood from the following discussion. The design of point-to-point DU transmission for high symbol rate DP WDM coherent systems is based on contours of the deterministic received SNR (for the worst-case reference channel of interest, normally the center WDM channel) versus both transmitted power P and number of spans N_s (see, e.g., [15]). An example of such deterministic SNR contours is given at $u=0$ and $u=1$ in Fig. 2: there we show the SNR contours at level $S_0=9.8$ dB for a point-to-point DP-QPSK WDM system (bit-error rate (BER) equal to 10^{-3} without differential decoding) over an $N_s\times 100$ km DU link with non-zero dispersion shifted fiber (NZDSF: dispersion $D=2$ ps/nm/km, attenuation $\alpha=0.2$ dB/km, $n_2=2.5\times 10^{-20}$ m^2/W, $A_{eff}=80$ μm^2 at $\lambda=1550$ nm) with either a