Design rules for reach maximization in uncompensated Nyquist-WDM links

Design Rules for Reach Maximization in Uncompensated Nyquist-WDM Links

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Abstract *We propose analytical design rules to predict relative maximum reach variations in NyWDM uncompensated links. Tradeoffs among system parameters are shown. Validation is demonstrated using experimental data. The method can be used also for comparison of different modulation formats.*

Introduction

The performance of uncompensated links based on Nyquist-WDM (NyWDM) and multilevel modulation formats with coherent receivers (Rx) is limited by the joint action of ASE noise, introduced by optical amplifiers, and nonlinear propagation disturbance, also referred to as nonlinear interference (NLI). In the technical literature, analytical models of NLI have been proposed [1,2] and extensively validated [3-5].

These models depend on system parameters but they do not directly provide scaling laws for the system reach, as required in preliminary design phases. To this purpose, we carried out a comprehensive analysis aimed at the definition of a simplified approximation of the GN-model [2], with a controlled maximum error. Then, we applied the simplified model to reach maximization of uncompensated links based on NyWDM, given the target BER and the optical bandwidth B_{opt}. We obtained a simple analytical expression clearly showing tradeoffs between main system parameters, i.e., target $OSNR$ (depending on modulation format and/or FEC), symbol rate R_s, channel spacing Δf, amplifier and fiber parameters. Validation was done by comparison with experimental results [3,4].

Theory

We considered a comb of N_{ch} NyWDM channels at symbol rate R_s with spacing Δf over B_{opt} (see Fig. 1). N_{ch} was consequently set to $N_{ch}=B_{opt}/\Delta f$. P_{ch} was the power per channel. The link was made of N_s spans with span loss A_s, including fiber and extra losses. A_s[1] was completely recovered by an EDFA with noise figure F.

Transmission is limited by ASE noise and NLI that practically accumulate linearly with distance [2] and BER is determined by the Rx nonlinear SNR (i.e., $OSNR_{NL}$ [2] in a noise bandwidth $B_n=R_s$):

$$SNR_{NL} = \frac{E_{ch}}{N_S\left(G_{ASE}+G_{NLI}\right)} \qquad (1)$$

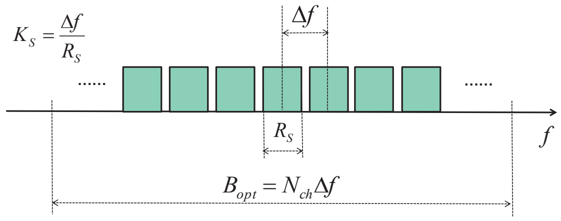

Fig. 1: Considered NyWDM transmitted spectrum

where $E_{ch}=P_{ch}/R_S$ is the channel energy, $G_{ASE}\approx F\cdot h\cdot f_0\cdot A_s$ is the ASE noise power spectral density, h is Planck's constant, f_0 is the NyWDM center frequency. On the center NyWDM channel, NLI can be expressed as a white and *Gaussian* additive noise whose power spectral density is [2]:

$$G_{NLI} \cong \frac{8}{54} C\cdot \text{asinh}\left\{\frac{\pi}{C}\frac{|D|R_S^2}{\alpha_{dB}}\left[\frac{B_{opt}}{K_S R_S}\right]^{\frac{2}{K_S}}\right\}\frac{\alpha_{dB}}{|D|}\gamma^2 L_{eff}^2 E_{ch}^3 \qquad (2)$$

where $K_s=\Delta f/R_s$, α_{dB} [dB/km] is the fiber loss parameter, D [ps/nm/km] is the dispersion parameter, γ [1/W/km] is the nonlinear coefficient, L_{eff} is the fiber-span effective length $C=2/5\cdot f_0^2/\log_{10}(e)/c$, and c is the speed of light.

Once the target BER is defined, it implies a target $SNR_T=SNR_{NL}$ independent of R_s, given the modulation format and Tx/Rx structure. Hence, substituting Eq. (2) into Eq. (1), the reach N_s vs. P_{ch} can be easily analyzed and the optimal power P_{opt} giving the maximum reach $N_{s,max}$ can be derived [2]. In order to get *quick* design rules clearly showing scaling laws of P_{opt} and $N_{s,max}$ with respect to system parameters we need to define an approximation of Eq. (2). To this purpose we considered the following approximation of the G_{NLI} expression:

$$G_{NLI} \cong K_{NLI}\frac{1}{K_S}\frac{\alpha_{dB}}{D}\gamma^2 L_{eff}^2 E_{ch}^3 \qquad (3)$$

where K_{NLI} is a system independent constant. In order to validate Eq. (3) we analyzed a wide range of system parameters (R_s ∈ [15;40] GBaud, F_{dB} ∈ [3;6] dB, $SNR_{T,dB}$ ∈ [10;20] dB, α_{dB} ∈ [0.15;0.25] dB/km, D ∈ [4;24] ps/nm/km, γ ∈

[1] We define losses as parameters ≥ 1, i.e., given loss A we assume $P_{out} = P_{in}/A$.

[0.5;2] 1/W/km) and evaluated the max reach using the exact - Eq. (2) - and approximated - Eq. (3) - G_{NLI} expressions. The maximum inaccuracy we observed was 0.5 dB. Hence, Eq. (3) demonstrated to be a good approximation of the NLI spectral density.

Using Eq. (3), it was possible to derive how P_{opt} and $N_{s,max}$ vary with respect to a reference scenario. Using convenient dB units, we obtained the variation of the optimal launched power vs. the variation of the key parameters:

$$\Delta P_{opt} = 10\log_{10}\left(\frac{P_{opt}}{P_{opt,ref}}\right) = \frac{1}{3}\left(\Delta\alpha + \delta A_S\right) + \frac{1}{3}\left(\Delta D - 2\Delta\gamma\right) + \frac{1}{3}\delta F + \frac{1}{3}\left(\Delta K_s + 3\Delta R_s\right) \quad [\mathrm{dB}] \qquad (4)$$

and the maximum reach ratio:

$$\Delta N_{s,\max} = 10\log_{10}\left(\frac{N_{s,\max,}}{N_{s,\max,ref,}}\right) = \frac{1}{3}\left(\Delta\alpha - 2\delta A_s\right) + \frac{1}{3}\left(\Delta D - 2\Delta\gamma\right) - \frac{1}{3}\left(3\delta SNR_T + 2\delta F\right) + \frac{1}{3}\Delta K_s \quad [\mathrm{dB}] \qquad (5)$$

where incremental parameters with respect to a reference scenario (subscript "*ref*") are:

- $\Delta\alpha = 10\cdot\log_{10}(\alpha_{dB}/\alpha_{dB,ref})$
- $\delta A_s = A_{s,dB} - A_{s,dB,ref}$
- $\Delta D = 10\cdot\log_{10}(D/D_{ref})$
- $\Delta\gamma = 10\cdot\log_{10}(\gamma/\gamma_{ref})$
- $\delta SNR_T = SNR_{T,dB} - SNR_{T,dB,ref}$
- $\delta F = F_{dB} - F_{dB,ref}$
- $\Delta R_s = 10\cdot\log_{10}(R_s/R_{s\,ref})$
- $\Delta K_s = 10\cdot\log_{10}(K_s/K_{s\,ref})$.

In both Eqs. (4) and (5), contributions can be grouped in 4 families, depending on:

- fiber- and span-loss (loss contribution);
- fiber dispersion and nonlinearity (fiber contribution);
- target performance and amplifier noise figure (noise contribution);
- symbol rate and channel spacing (spectral efficiency contribution).

From Eqs. (4) and (5) the following two fundamental properties can be derived.

- ΔP_{opt} does not depend on changes in SNR_T (see Eq. (4)): this means that the optimal power is independent of modulation format and/or FEC gain, given the link, the rate and the relative channel spacing.
- The maximum reach is independent of the rate, given target performance and relative channel spacing, as already shown in [6].

Validation

In order to obtain actual values, Eq. (4) and (5) need to refer to a reference scenario. In this work, we assumed to operate on B_{opt}~3 nm and the reference setup was the transmission of 9 PM-16QAM 200G channels over a L_s=80 km SSMF uncompensated link. We simulated such a system scenario obtaining $N_{s,max,ref}$=15. The reference BER was 10^{-3} corresponding to $SNR_{T,dB,ref}$ =16.85 dB. System parameters were: $\alpha_{dB,ref}$=0.22 dB/km, $A_{s,dB,ref}$=17.6 dB, D_{ref}=16.7 ps/nm/km, γ_{ref}=1.3 1/W/km, $F_{dB,ref}$=5 dB, $R_{s,ref}$=32 Gbaud, $K_{s,ref}$=1.05.

Tab. 1: Validation using experimental results

Exp	R_s [Gbaud] K_s	Fiber	$N_{s,max}$ Exp	$N_{s,max}$ Eq. (5)
Reference NyWDM 200G PM-16QAM	R_s=32 K_s=1.05	SSMF	15 (simulation result)	
[3] NyWDM 100G PM-QPSK	R_s=30 K_s=1.1	NZDSF	8	7
		SSMF	20	20
		PSCF	32	31
[4] NyWDM 100G PM-16QAM	R_s=15.625 K_s=1.024	NZDSF	12	11
		SSMF	38	39
		PSCF80	44	45
		PSCF110	58	57
		PSCF130	62	63
		PSCF150	70	70

In order to validate our approach, we considered data of already published experimental results, and for such setups we used Eq. (5) to evaluate ΔN_s with respect to the reference scenario. Then, we estimated the maximum reach as

$$N_{s,max} = N_{s,max,ref}\cdot 10^{\frac{\Delta N_s}{10}} \qquad (6)$$

displaying the results in Tab. 1.

The first considered experiment [3] was a 10-channel NyWDM 100G PM-QPSK setup (R_s=30 GBaud, K_s=1.1) comparing max reach of 3 fibers at BER=10^{-3} ($SNR_{T,dB}$=12.7 dB). The second one [4] was a 22-channel NyWDM 100G PM-16QAM setup (R_s=15.625, K_s=1.024) that investigated the max reach over 7 different fiber types at BER=10^{-2} ($SNR_{T,dB}$=17.3 dB). Regarding the second experiment, we did not consider DCF results as this fiber parameters are out of the ranges considered in this work. For the other fibers, besides the parameters listed in [4], we included the following measured insertion extra losses: 2 dB (NZDSF), 0 dB (SSMF), 0.3 dB (PSCF80), 0.4 dB (PSCF110), 0.6 dB (PSCF130 and PSCF150).

As it can be observed in Tab. 1, the prediction accuracy based on Eq. (5) with respect to the experimental results is always within 1 span. It confirms the reliability of the proposed method, even when applied to different modulation formats and rates. Reliable application to a wide range of fiber types is clearly shown as well.

Example of scaling laws

Considering the same reference scenario as in the previous section, we used Eq. (5) to evaluate $\Delta N_{s,max}$ vs. the variation of the key system parameters, over a wide range. Results are in Fig. 2.

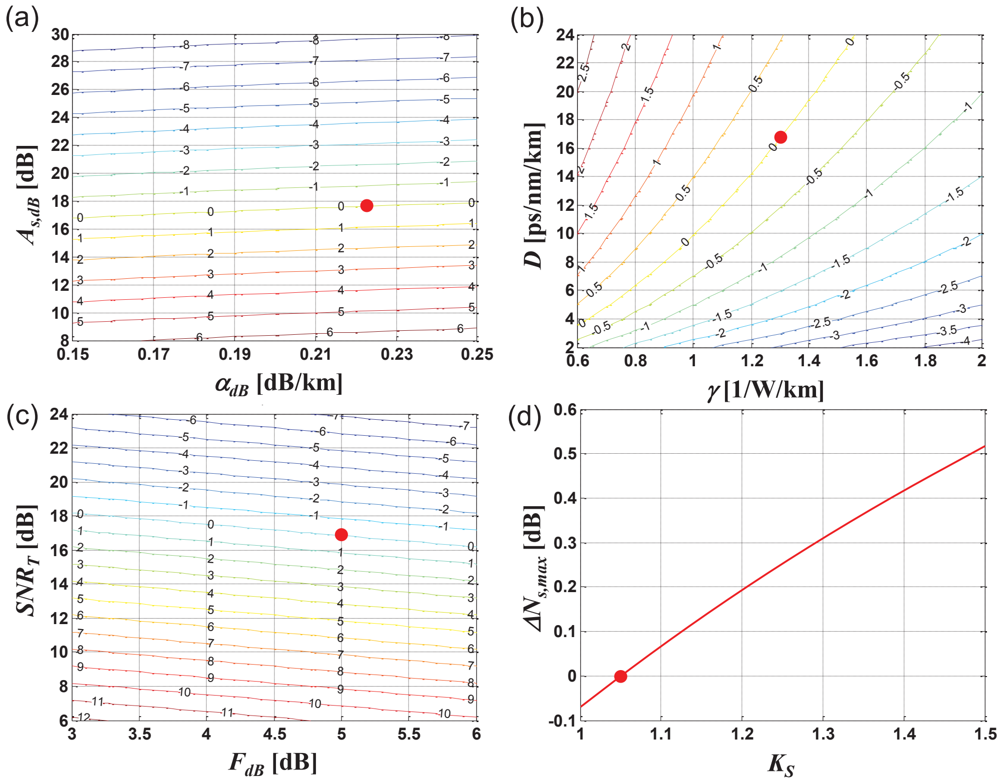

Fig. 2: Loss contribution to $\Delta N_{s,max}$ vs. fiber- and span-loss (a). Fiber contribution to $\Delta N_{s,max}$ vs. nonlinearity and dispersion (b). Noise contribution to $\Delta N_{s,max}$ vs. amplifier noise figure and target SNR (c). Spectral efficiency contribution to $\Delta N_{s,max}$ vs. normalized channel spacing K_s (d). Red spots refer to the reference scenario.

Loss contribution (Fig. 2a)

Given $A_{s,dB}$, a reduction of α_{dB} induces a weak performance worsening due to L_{eff} enlargement. A smaller α_{dB} implies also benefits as possible L_s extending and/or tolerable extra loss increasing, keeping $A_{s,dB}$ constant. The effect of $A_{s,dB}$ variation is mitigated by a factor 2/3: to double the reach, we need to reduce $A_{s,dB}$ by 4.5 dB.

Fiber contribution (Fig. 2b)

The larger is D, the better is the performance, while the opposite is true for the nonlinearity coefficient γ, but the weight of each parameter is different. Max reach sensitivity to γ is double with respect to D. For instance, doubling dispersion means 25% (1 dB) reach extension, while doubling nonlinearity means 37% (2 dB) reach shrinking.

Noise contribution (Fig. 2c)

$SNR_{T,dB}$ is the only parameter affecting max reach without mitigation, i.e, 3 dB reduction means doubling of max reach, whereas F_{dB} has a mitigated effect, as we need 4.5 dB reduction to get reach doubling. $SNR_{T,dB}$ is dependent on both the modulation format and FEC strength, being $SNR_{T,dB}$=$SNR_{T,dB,UC}$–$G_{FEC,dB}$, where $SNR_{T,dB,UC}$ is the SNR requirement without coding and $G_{FEC,dB}$ is the FEC gain. The FEC gain goes directly into reach extension but its drawback is a loss of spectral efficiency (*SE*) and consequently of channel capacity, given B_{opt}.

Spectral efficiency contribution (Fig. 2d)

Reducing *SE* through Δf increasing gives benefit up to 0.6 dB (15% reach extension) going from no guard-band (K_s=*1*) to 50% guard-band (K_s=*1.5*). Of course capacity is adversely affected.

Conclusions

Based on the GN-model of nonlinear propagation [1,2], we proposed a simple analytical method to predict the optimal power and max reach variations in NyWDM uncompensated links. We derived simple scaling rules vs. key system parameters, which we validated both by simulation and experimentally. The proposed method proved to be effective for different rates and modulation formats on a wide range of transmission fibers.

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