# Multi-level optimization of a fiber transmission system via nonlinearity management

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**Abstract:** Nonlinearity management is explored as a complete tool to obtain maximum transmission reach in a WDM fiber transmission system, making it possible to optimize multiple system parameters, including optimal dispersion pre-compensation, with fast simulations based on the continuous-wave approximation.



**OCIS codes:** (060.2330) Fiber optics communications; (060.4370) Nonlinear optics, fibers

## References and links

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## 1. Introduction

In addition to many other attractive features such as reducing noise and being applicable to any spectral band, distributed Raman amplification offers the possibility to manage the signal power evolution along the transmission span. Indeed, the possibility of exerting control over the signal power profile and perform direct nonlinearity management [1-4] allows for the balancing of the penalties originated from noise accumulation and from nonlinear impairments, thus leading to increased system reach or expanded performance margins [5].

Despìte the many advantages that can be derived from implementing distributed amplification in optical transmission systems, the introduction of new degrees of freedom for system optimization make finding the best possible configuration a daunting task. In this paper we present a detailed discussion of the successive steps involved in the application of the nonlinearity management technique to transmission system optimization, including dispersion pre-compensation.

In previous works [3-11], a variety of optimization approaches have been proposed and discussed. In the methodology proposed here we develop and combine for the first time different techniques into a coherent, detailed and self-contained strategy for the optimization of an entire optical transmission system. This new strategy presents a number of inherent advantages, such as allowing to determine many of the important optimal parameters without having to perform any time-consuming transmission simulation based on amplitude equations.

For illustration, but without loss of generality, we consider a WDM transmission system with hybrid Raman/EDFA amplification. The basic cell of our system is schematically depicted on Fig. 1: a span of standard single-mode fiber (SSMF) is followed by a -100 ps/nm/km dispersion-compensating fiber (DCF) module. Distributed Raman amplification (DRA) with bi-directional pumping is used in the SSMF section, whereas an Erbium-doped fiber amplifier (EDFA) with a noise figure of 4.5 dB provides additional amplification at the end of the span. We shall consider a wavelength-division multiplexed (WDM) transmission, with 16-channels. The SSMF span length is not fixed, but rather it is one of the multiple system design parameters that will be subject to our optimization procedure.

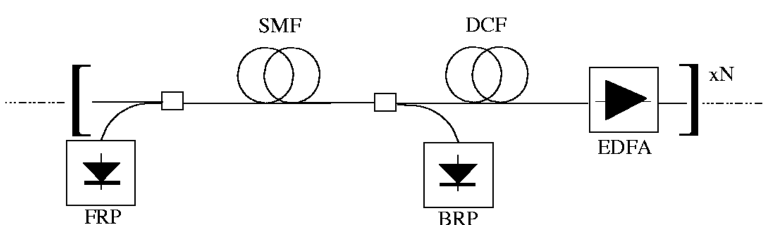


Fig. 1. System Schematic.

## 2. Optimization of the amplification scheme/span length

Following the approach that was presented in refs. [3,4], the first step involves optimising the amplification scheme in terms of two key parameters. Namely: $\eta_1$ which is the ratio between Raman gain and total span gain (to compensate for total span loss), and $\eta_2$ which is the ratio between the backward and total Raman pump powers in the SSMF. Nonlinear impairments are qualitatively assessed by calculating the channel nonlinear phase shift (NPS) per span, whereas the system output optical signal-to-noise ratio (OSNR) over 1 nm measures the impact of noise accumulation. Given that a full optimisation analysis requires taking into account both span length (i.e., the length L of the SSMF) and output OSNR, we are facing a complex 4-dimensional optimization problem that we are solving in the frame of the well known CW model for the evolution of the average powers of signals and pumps (including double-Rayleigh backscattering and amplified spontaneous emission as sources of noise) [12].

As a key optimization parameter, the function NPS ($\eta_1$, $\eta_2$, L) is computed for multiple values of the output OSNR level. We fix the total transmission distance to an arbitrary long

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length (e.g., to 900 km), so the number of spans will be adjusted automatically as we vary the span length L. Figure 2 shows the NPS vs. $\eta_1$ and L for a value of $\eta_2$ equal to 1 and an OSNR of 20 dB at the receiver (i.e., after the total transmission distance).

By drawing a series of such plots, sweeping through different values of $\eta_2$ (see animation associated to Fig. 2) and of the OSNR, we can find the span length and amplifier configuration that minimize the NPS for any given value of the OSNR (please note that since we will consider all possible target OSNRs, the initial choice of total transmission length used to produce the contour plots becomes irrelevant). So far the input signal power is a free parameter, to be adjusted in order to achieve the target OSNR at a given system reach.

Both the optimal span length and $\eta_1$ depend quite strongly on the pump split ratio characterized by $\eta_2$. With full forward Raman pumping ($\eta_2 = 0$, not see animation), a short span length of about 30 km SSMF and a 50% splitting of the gain between Raman and EDFA (i.e., $\eta_1 = 0.5$) amplifiers give the best system performance. The optimal span length and relative contribution from the Raman amplifier to the total gain increase gradually as the backward Raman pump grows larger until $\eta_2$ reaches a value of 0.75, for which the optimal span length is 60 km and the optimal $\eta_1$~0.6. Finally, for $\eta_2 = 1$ (as shown in Fig. 2), the optimal span length decreases to 50 km, again with an optimal $\eta_1$~0.6.

By considering the optimum solution for each possible value of $\eta_2$, we see that nonlinear penalties are reduced (always at the same OSNR level of 20 dB) as the gain contribution from forward Raman pumping decreases. The best result for the whole 3-dimensional space defined by a fixed value of the OSNR is then obtained for: $\eta_1 = 0.6$, $\eta_2 = 1$, and L = 50 km.

Note that, working under the assumption that the minimization of the cumulated fiber nonlinearity represents the best situation in terms of system performance, the determined optimal set of parameters $\eta_1$, $\eta_2$ and L for any given OSNR level can be considered to be independent of the transmission format. Moreover, as expected from previous work, this optimal configuration for the particular system under study is largely invariant to OSNR requirements: for example, target OSNRs>15 dB lead to the same optimal configuration discussed above, which allows us to conclude the optimization of the span length/amplifier gain distribution. Please note that these optimal parameters have been determined within the frame of the CW model, and without having to resort to lengthy full transmission simulations, greatly reducing computational time. Our procedure can be equally applied in practice to solve constrained optimization problems, for example when a system provider requires a span length L larger than a given value.

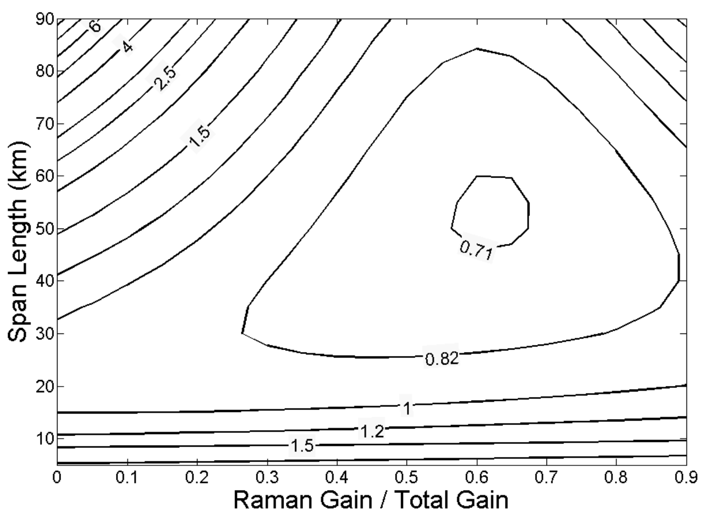


Fig. 2. NPS vs. $\eta_1$ and $L$, with $\eta_2 = 1$, for an OSNR of 20 dB after 900 km (Animation shows results for different values of $\eta_2$)

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We have now obtained the values of $\eta_1$, $\eta_2$ and L that will produce the best performance, but the optimal input signal power level (which will dictate the optimal OSNR level) is yet to be determined. Unlike the previous characteristics, the optimal input signal power is heavily dependent on the signal's relative tolerances to noise and nonlinearities, and as such it is strongly format-dependent. In order to obtain it, it is necessary to perform full transmission simulations, adapted to the particular transmission format and channel configuration. In these simulations, we have just one degree of freedom to find the optimal solution (i.e. launched signal power into the optimized span), which reduces computational time. We can determine in this way the maximum transmission distance, in this case focusing on the performance of the central channel (channel 8). In our example, the modulation format was on-off keying with RZ-50% Gaussian pulses at 40 Gbit/s per channel, with Q-factors averaged over multiple runs using pseudo-random bit patterns of $2^9$-1 bits. For this transmission format, the optimal input power was $P_{in}$~ -10 dBm, and the error-free total transmission length (calculated by including both SSMF and DCF lengths, and determined by a Q-factor above 6) was in excess of 1400 km without any dispersion pre-compensation. Such low optimal average power is obtained thanks to the bi-directional distributed amplification in the SSMF, which prevents the signal from dropping to noise levels. Figure 3 depicts the results of these transmission simulations in terms of reach vs. span length and input power, thus providing an independent confirmation of the existence of an optimal span length of 50 km. Please note that although in our particular case increasing the bit sequence length did not result in a visible improvement in the precision of our results, for different configurations longer sequences may be required in order to accurately account for nonlinear transmission penalty [13].

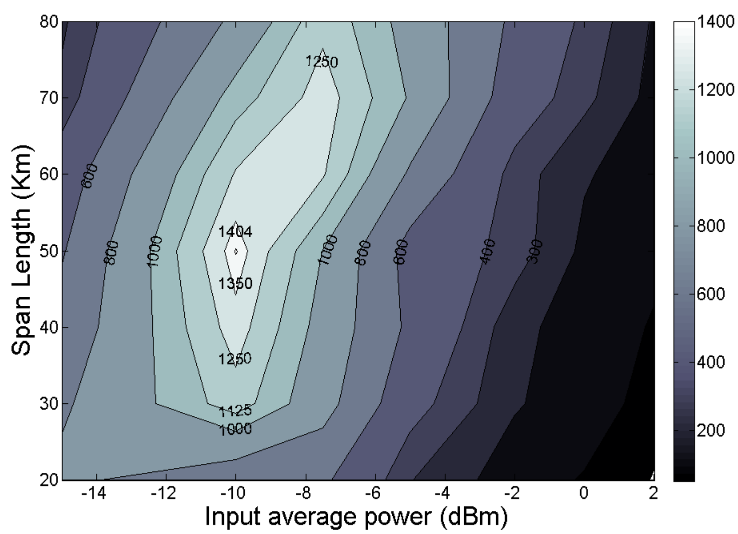


Fig. 3. Max reach (Km) vs. Span length and input power for 16-channel OOK RZ-50% transmission, with no dispersion pre-compensation or average dispersion optimization.

### 3. Optimization of the pre-compensation length

Finding the optimal pre-compensation for a given transmission system is essential in order to minimise the impact of both intra-channel and inter-channel distortions. In Ref. [7], Killey *et al*. provided a simple criterion for optimum pre-compensation in dispersion-managed systems with lumped amplification that has been confirmed for on-off keying systems with direct detection. Namely, the $D_{pre}$ should be chosen so that pulses are compressed to a minimum duration at a distance *z'* within the nonlinear length of each span, where

$$\int_0^{z'} P_{in} e^{-\alpha_S z} dz = \int_{z'}^{L} P_{in} e^{-\alpha_S z} dz \,, \tag{1}$$

with $D_{pre}$ = -$D_{SMF}$ $z'$, from which

$$D_{pre} = \frac{-D_{SMF}}{\alpha_S} \ln\left(\frac{2}{1+e^{-\alpha_S L}}\right) - \frac{ND_{res}}{2}. \tag{2}$$

$D_{res}$ is the residual dispersion if average dispersion is different from zero, and $N$ represents the number of spans. Such optimal $D_{pre}$ minimizes both pulse overlap within the nonlinear length, and maximizes the reversal of timing jitter build-up in the second half of the nonlinear span. In the case of a system with distributed amplification, signal power evolution within the span is not trivial, but the above procedure can be still generalized and an equivalent relation can be obtained which is valid for any amplification scheme:

$$\int_0^{z'} P_S(z)dz = \int_{z'}^{L} P_S(z)dz \tag{3}$$

where $P_S$ can be analytically estimated only if pump depletion is neglected.
In general, it will be simpler to obtain the optimal distance $z'$ by numerically integrating the signal power and finding the z' that verifies the above condition. This is equivalent to finding the point within the SSMF where the accumulated NPS reaches half of its total value, or the NPS barycentric, as proposed in [8]. This simple procedure permits to find the optimal pre-compensation length for any given amplifier configuration and span length, once again without the need for time-consuming full system simulations. For illustration, Fig. 4 shows in a contour plot the optimal pre-compensation lengths (in km) of DCF, superimposed on top of the NPS vs. $\eta_1$ and L, for the case of $\eta_2$ = 1, a target OSNR of 20 dB at 900 km, and 16 WDM channels.

From Fig. 4, it is easy to see that the optimal pre-compensation length for the best system configuration ($\eta_1$ = 0.6, $\eta_2$ = 1, and L = 50 km) is approximately equal to 3.8 km, instead of the 2.2 km that would have been predicted by (2) . Note that Killey *et al's* method for calculating the pre-compensation length in lumped amplification systems is obtained under the assumption that nonlinearities are accumulated in the transmission span only, and not in the DCF. This hypothesis is still valid in the present case involving DRA in the SSMF, and loss in the DCF.

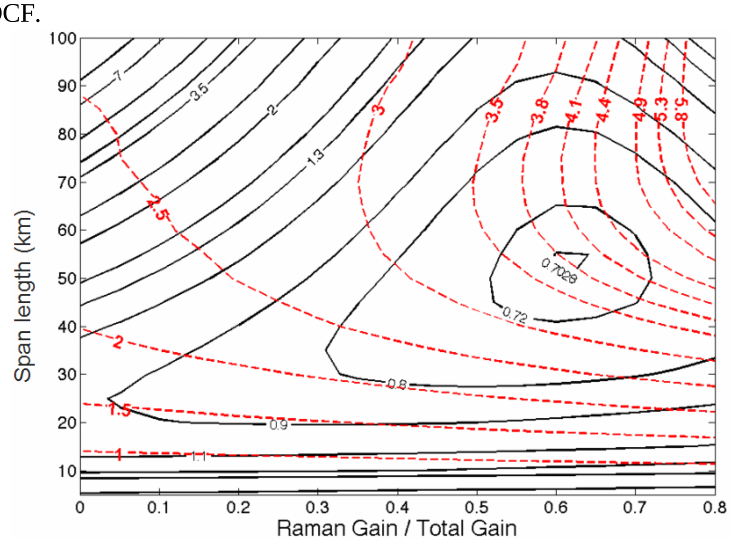


Fig. 4. Optimal pre-compensation lengths (red dash) and accumulated NPS (black) vs. $\eta_1$ and $L$, for the case of $\eta_2$ = 1 OSNR = 20 dB

In order to verify and confirm the accuracy of the optimal pre-compensation criterion discussed above, we carried out full numerical transmission simulations where we monitored


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the maximum transmission distance for channel 8 vs. pre-compensation DCF length. Our aim here was to find the best system configuration for the 16-channel OOK RZ-50% Gaussian signal transmission at 40 Gbit/s per channel.

As shown in Fig. 5, these simulations confirm that the optimal length of pre-compensation DCF (for zero average system dispersion) is between 3.8 km and 4 km. Such pre-compensation enables an increase in the transmission distance for channel 8 from 1400 up to 1755 km. In addition, as shown in Fig. 5, we observed as expected, a drift in the optimal pre-compensation length towards shorter DCFs as the absolute value of (negative) span average dispersion is increased by varying the length of the DCF on each span. The DCF used is designed to match both the dispersion and dispersion slope accumulated in the SMF, so similar amounts of residual dispersion are accumulated in all the channels. As it can be seen, however, the observed drifting is slower than what is predicted by Killey's correction factor of $-ND_{res} / 2$. Indeed, we have verified that the drift is directly dependent on the amplification configuration, defined by parameters $\eta_1$ and $\eta_2$. This fact suggests that the nonlinear signal evolution along the span modifies its response to accumulated dispersion, and highlights the need for further adjustment of the correction term when applying the pre-chirp selection rule to systems with non-zero average dispersion using distributed or hybrid amplification. For the configuration under study here, we achieved a maximum transmission distance (measured over SSMF and DCF) of 2164 km with an average dispersion of -0.3 ps/nm/km, and a pre-compensation length of 1.5 km.

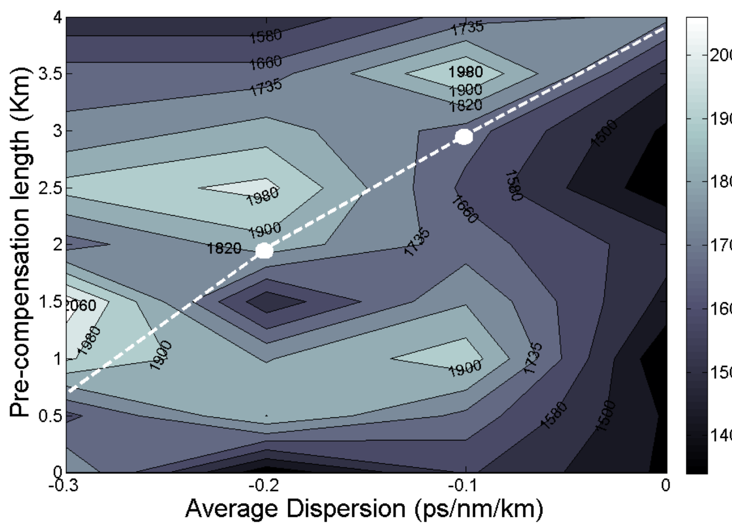


Fig. 5 Reach (Km) vs. pre-compensation length and average dispersion for the optimal span configuration and input average power. White dashed line: expected drift with average dispersion according to Killey's formula.

## 4. Conclusion

We have presented a new coherent and self-contained strategy for the optimization of optical transmission links, relying on the use of nonlinearity management theory. A step-by-step example of the implementation of this strategy on a hybrid amplification transmission system has been detailed. Our nonlinearity-management based approach allows for important sections of the full optimization, such as the determination of the best span length, amplifier configuration, and pre-compensation length, to be accomplished rapidly and efficiently in links with either lumped, distributed or hybrid amplification, by means of simple numerical simulations devised within the framework of the continuous-wave approximation for the transmitted signal, leading to greatly reduced computational times when compared to lengthy NLSE-based optimization procedures.

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