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New method to obtain optimum performance for 100Gb/s multi-span fiber optic lines

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ABSTRACT

Design of DWDM lines requires calculation of optimal input powers for each span. It is called “optimization of DWDM network”. Different approaches are currently used to solve this task including maximization of optical signal-to-noise ratio (OSNR) margin and minimization of bit error rate (BER). Within last years there is a particular interest to DWDM lines based on uncompensated links with coherent transmission. We analyze benefits and drawbacks of existing approaches and offer a new method of optimization that guarantees sufficient OSNR margin for bringing into service such DWDM lines.

The proposed method combines the advantages of two previously known methods. For short lines, it works like BER criterion. It does not overestimate values of power, and does not require the recalculation after each stage of expansion of the line. For long lines, it works like OSNR margin criterion. It guarantees that calculated values of powers will enable bringing the line into service; and if the optimization is failed it means that it is impossible to commission the line by any other method.

Discussion and comparison of different methods are based on a general phenomenological model for multi-span fiber optic line that takes into account both linear and nonlinear noises. The proposed phenomenological model is a consequence of the GN model where a number of parameters characterizing nonlinear interaction of DWDM channels are determined experimentally.

1. Introduction

In last decades the fiber optic communication lines became the dominant medium of information exchange between cities, regions, countries and continents. Capacity of the modern commercial Wavelength-Division Multiplexed (WDM) systems achieves dozens of Terabit/s with transmission distances of more than a thousand kilometers in multi-span lines [1–5] and more than 500 km in single-span lines [6–8]. Nevertheless, an efficient design of high speed optical transmission systems or optical networks at lowest cost with ever increased throughput or reach is a big challenge. It requires very subtle knowledge of the interplay of multiple physical phenomena, and effective engineering rules to deal with the complexity of a whole system. Indeed, numerous physical effects of different natures can impact propagation over optical fiber links, such as fiber attenuation, noise, chromatic dispersion, Kerr effects, Polarization Mode Dispersion, Stimulated Raman scattering and others [9–12].

Convenient rules and optimization criteria have been developed for calculation and optimization of transmission systems with speeds of 10 Gb/s and 40 Gb/s based on the amplitude (ASK) or differential phase (DPSK) modulations and fiber optic lines with dispersion compensation. These rules and criteria are based on using semi-empirical models such as cumulated nonlinear phase model [13] and weighted non-linear phase model [14,15]. Their relevance in capturing the impact of accumulated nonlinearities in a dispersion-managed transmission system was demonstrated [16]. These rules and criteria are widely used for designing of communication lines with dispersion compensation.

An implementation of coherent communication systems has resulted in dramatic and revolutionary changes in optical transmission systems. Complete or almost complete elimination of the need for compensation of chromatic dispersion along a communication line became one of many consequences of implementation of coherent systems and use of digital signal processing (DSP) in real time. An absence of dispersion compensating units (DCUs) decreases the quantity of amplifiers and power consumption, and significantly reduces a total delay of signal during the propagation in a communication line.

Uncompensated transmission (UT) drastically changes the character of propagation of optical signals and the nature of nonlinear distortions. In uncompensated coherent systems a

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plenty of symbols overlaps and interferes that leads to pseudorandom shape of temporal envelope; and accumulation of nonlinear effects can be described using a Gaussian noise model (GN model) [21]. As a result, traditional methods of calculation and design of non-coherent communication systems appeared to be inapplicable for coherent lines without dispersion compensation.

Simple analytical expressions were obtained in a theoretical model based on perturbation theory that proved to be very usable for analysis of fiber optic transmission systems without periodical dispersion compensation [17–24]. In this model nonlinear distortions are regarded as a nonlinear interference noise. A methodology of construction of fiber optic lines with maximal reach was developed based on this model [26,27], but the calculations are performed without taking into account a telecom operators' requirement to provide some OSNR margin that is required for commissioning of the line [28].

In this article, we offer a new method of optimization of fiber optic lines that enables achieving of the maximal reach of the designed line with guaranteed OSNR margin that is required for successful commissioning of the commercial fiber optic lines [28].

2. Phenomenological model of a multi-span line

It was shown in a number of articles that nonlinear distortions in fiber optic line can be treated as nonlinear noise P_{NL} which is additive to the noise of amplified spontaneous emission P_{ASE}: $P_{\Sigma} = P_{NL} + P_{ASE}$, where P_{Σ} is a total noise influencing on BER [17,19]. Turning from the absolute values of noises to signal-to-noise ratios, this formula can be written as follows:

$$\frac{1}{OSNR_{BER}} = \frac{1}{OSNR_L} + \frac{1}{OSNR_{NL}}. \tag{1}$$

All values of powers in this formula should be reduced to the beginning of the span.

The value of linear noise of amplifier (in the end of the span) is determined by a formula $h\nu B(GF-1) \approx h\nu BGF$, where B is normalized bandwidth, G is gain of the amplifier and F is EDFA's noise figure. If we reduce it to the beginning of the span we will get value $h\nu BAF$, where A is a span attenuation. We will use a short notation $C \equiv h\nu BAF$, so we can write:

$$\frac{1}{OSNR_L} = \frac{C}{P}. \tag{2}$$

The value of nonlinear noise in the line depends on a signal power P by a phenomenological rule $P_{NL} = \eta P^3$, where η is a nonlinearity coefficient, which depends on fiber span and does not depend on signal power, so we can write:

$$\frac{1}{OSNR_{NL}} = \eta P^2. \tag{3}$$

A criterion of the line operability can be expressed with the formula $OSNR_{BER} > OSNR_{BTB}$, where $OSNR_{BTB}$ is a minimal signal-to-noise ratio that is required for transponder to receive signal in a "back-to-back" configuration. $OSNR_{BTB}$ is a constant value that characterizes a quality of the receiver. Using the formula (1) the criterion of the line operability can be written as follows:

$$\frac{1}{OSNR_L} < \frac{1}{OSNR_{BTB}} - \frac{1}{OSNR_{NL}}. \tag{4}$$

To denote an expression in the right part of the inequality (4) the value $OSNR_R$ is introduced, which is defined as follows:

$$\frac{1}{OSNR_R} \equiv \frac{1}{OSNR_{BTB}} - \frac{1}{OSNR_{NL}}. \tag{5}$$

In other words, $OSNR_R$ is a minimal signal-to-noise ratio that is required for transponder to receive signal in a particular line at some value of signal power P. The value $OSNR_R$ is always greater than the value $OSNR_{BTB}$ due to influence of nonlinear noises, and increases with increasing of the signal power P. The difference between $osnr_R$ and $osnr_{BTB}$ in logarithmical units is called nonlinear penalty.

Using (5) the criterion of the line operability (4) can be rewritten as follows:

$$\frac{OSNR_L}{OSNR_R} > 1. \tag{6}$$

Or in logarithmical units: $osnr_L > osnr_R$.

To denote an expression in the left part of the inequality (6) the value $OSNR_M$ (OSNR margin) is introduced, which is defined as follows:

$$OSNR_M \equiv \frac{OSNR_L}{OSNR_R}. \tag{7}$$

Thus the criterion of the line operability can be written in the following form: $OSNR_M > 1$. Or in logarithmical units: $osnr_M > 0$.

All values introduced above are shown on Fig. 1. A logarithmical representation is more convenient to show the value $osnr_M$ in explicit geometric form (Fig. 1a), while a representation in absolute values is more convenient to show the value $1/OSNR_{NL}$ in explicit geometric form (Fig. 1b).

Values $OSNR_{BTB}$, $OSNR_L$ and $OSNR_R$ (and $OSNR_M$ respectively) can be measured using optical spectrum analyzer (OSA). In order to measure $OSNR_R$, an additional noise is added into the line until the line failure; the measured signal-to-noise ratio in this moment is

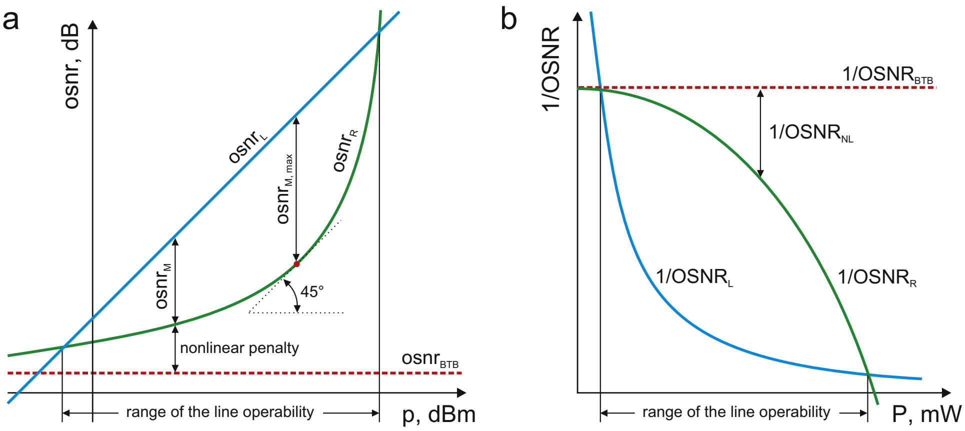

Fig. 1. Basic values used to describe the fiber-optic communication lines taking into account the nonlinear noise.

Table 1
Parameters of the line.

Parameter	Value	Dimension
α	0.2	[dB/km]
L	100	[km]
NF	6	[dB]
η	20	10^{-5} [mW^{-2}]
$osnr_{BTB}$	12.4	[dB]

Note. Non-linearity coefficient η corresponds to a line with one channel 100 Gb/s.

$OSNR_R$. Knowing the $OSNR_R$ and $OSNR_{BTB}$ for different signal powers, it is possible to plot the dependence of $1/OSNR_{NL}$ on P^2 using the formula (5), check the phenomenological rule (3) and calculate η.

One can also calculate η using (1). The value $OSNR_{BER}$ can be determined by a level of bit error rate (BER) of the transponder using the waterfall curve of transponder (which represents the dependence of BER before FEC on OSNR measured in a “back-to-back” scheme), the value $OSNR_L$ can be measured using OSA. This method does not require adding additional noise into the line.

3. Optimization of a multi-span line with equal spans

The criterion of operability of the line $OSNR_{BER} > OSNR_{BTB}$ can be written using (1–3) as follows:

$$\frac{C}{P} + \eta P^2 < OSNR_{BTB}^{-1}. \tag{8}$$

If the length of the line (and parameter C accordingly) exceeds a certain limit, then the condition (8) is not satisfied for any value of the input power – the line is inoperable. If the length of the line is less than the critical length, then the condition (8) is satisfied for a range of powers $\{P_{MIN}, P_{MAX}\}$; in this case the task of determining of an optimal input power for the line (or for each span in multi-span line) arises. The solution of this task is called “an optimization of the line”.

General principles of optimization of a single-span line are presented in [25]. Planning strategies for multi-span networks are analyzed in [26,27].

Historically, a maximization of $OSNR_M$ value (6) and (7) was used as the first criterion for optimization of a line. The maximization of $OSNR_M$ allows achieving maximal resistance of the line to additional attenuations that can be inserted during the operation of the line (due to bends and degradations of the fibers, air gaps when disconnecting and connecting optical connectors, etc.). The value $OSNR_M$can be measured directly during the line commissioning that is also a benefit of this method.

The task of maximization of the value $OSNR_M$ is solved simply if the line consists of N equal spans. In such case we can accept as a first approximation [23]:

$$C(N) = N\,C_1$$

$$\eta(N) = N\,\eta_1$$

To find an optimal power using $OSNR_M$ criterion we need to find a maximum of the function:

$$OSNR_M = \frac{OSNR_L}{OSNR_R} = OSNR_L\left(\frac{1}{OSNR_{BTB}} - \frac{1}{OSNR_{NL}}\right)$$

$$= \frac{P}{NC_1}\left(\frac{1}{OSNR_{BTB}} - N\eta_1 P^2\right).$$

It is achieved when the input power equals to the following value:

$$P_M = \left(3N\eta_1 OSNR_{BTB}\right)^{-1/2}. \tag{9}$$

In logarithmical units:

$$p_M = -\frac{1}{2}\left(10\lg 3 + 10\lg\left(N\eta_1\right) + osnr_{BTB}\right) = p_{M,1} - 5\quad \lg\ (N) \tag{10}$$

where

$$p_{M,1} = -\frac{1}{2}\left(10\lg 3 + 10\ \ \lg(\eta_1) + osnr_{BTB}\right). \tag{11}$$

Another possible criterion of optimization of the line is minimization of the bit error rate (BER) level. This is equivalent to the maximization of $OSNR_{BER}$, i.e. the function in the left part of inequality (8). This function achieves maximum when the input power equals to the following value:

$$P_B = \left(\frac{C}{2\eta}\right)^{1/3} = \left(\frac{h\nu BAF}{2\eta}\right)^{1/3}. \tag{12}$$

In logarithmical units:

$$\begin{aligned} p_B &= \frac{1}{3}(-58 + \alpha L + NF - 3 - 10\lg(\eta)) \\ &= \frac{1}{3}(-61 + \alpha L + NF - 10\lg(\eta)). \end{aligned} \tag{13}$$

By substituting specific parameters (see Table 1) in formulas (11–13), we can draw graphs of dependence of optimal powers on the number of spans, Fig. 2.

The number of spans when two optimal powers are equal (in our case, $N = 70$) defines the critical length of the line (in our case, 7000 km). For lines that operate near the limit of operability, the optimal power on the BER criterion is close to the optimal power on the $OSNR_M$ criterion ($P_{MIN} \cong P_B \cong P_M \cong P_{MAX}$).

For lines which length is less then critical length, the optimal power on the $OSNR_M$ criterion is always greater than the optimal power on the BER criterion. Thus the optimization of the line using the BER criterion allows using less powerful amplifiers and building more cost-effective lines accordingly (although with a smaller resistance to the possible line degradation in future).

4. Optimization of a multi-span line with non-equal spans

In real multi-span lines spans (in general) are not equal. To solve the optimization problem of a generalized multi-span line we can use the property of addition of linear and nonlinear noises for multiple spans as a first approximation:

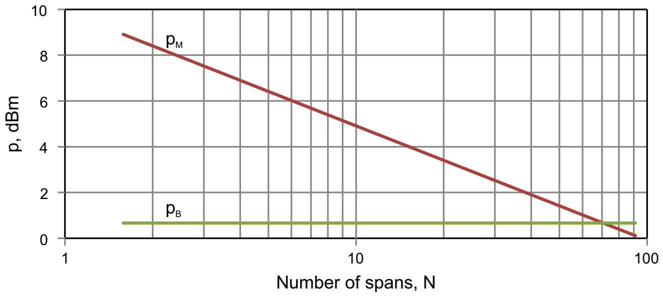

Fig. 2. Dependence of optimal powers p_M and p_B on the number of spans (for a line with equal spans).

$$\frac{1}{OSNR_L}=\sum_{n=1}^{N}\frac{1}{OSNR_{L,n}}=\sum_{n=1}^{N}\frac{C_n}{P_n}=\sum_{n=1}^{N}\frac{h\nu BA_nF_n}{P_n}. \qquad (14)$$

$$\frac{1}{OSNR_{NL}}=\sum_{n=1}^{N}\frac{1}{OSNR_{NL,n}}=\sum_{n=1}^{N}\left(\eta_nP_n^2\right). \qquad (15)$$

For optimization of a multi-span line with non-equal spans using *BER* criterion it is necessary to find a minimum of the function:

$$\frac{1}{OSNR_{BER}}=\sum_{n=1}^{N}\left(\frac{1}{OSNR_{BER,n}}\right)=\sum_{n=1}^{N}\left(\frac{C_n}{P_n}+\eta_nP_n^2\right). \qquad (16)$$

An optimal power for each span is calculated similarly to the formula (12) and does not depend on parameters of the other spans. It is convenient in practical use since there is no need to recalculate optimal powers for working spans during the development of the line and adding new spans.

For optimization of a multi-span line with non-equal spans using $OSNR_M$ criterion it is necessary to find a maximum of the function:

$$OSNR_M=\frac{\frac{1}{OSNR_R}}{\frac{1}{OSNR_L}}=\frac{\frac{1}{OSNR_{BTB}}-\frac{1}{OSNR_{NL}}}{\frac{1}{OSNR_L}}=\frac{\frac{1}{OSNR_{BTB}}-\sum_{n=1}^{N}\left(\eta_nP_n^2\right)}{\sum_{n=1}^{N}\left(\frac{C_n}{P_n}\right)}. \qquad (17)$$

Omitting the calculations, we give an answer:

$$P_{M,n}=\left(\frac{C_n}{\eta_n}\frac{OSNR_{M,\max}}{2}\right)^{1/3}. \qquad (18)$$

where $OSNR_{M,\max}$ is a maximal possible value of $OSNR_M$ for the given parameters of the line:

$$OSNR_{M,\max}=2\left(3\times OSNR_{BTB}\sum_{n=1}^{N}\left(C_n^2\eta_n\right)^{1/3}\right)^{-3/2}. \qquad (19)$$

Formulas (18) and (19) show that an optimal power for each span on the $OSNR_M$ criterion in a line with non-equal spans depends on parameters of all spans in the line. Therefore it is necessary to recalculate optimal values of $P_{M,n}$ for all spans if new spans are added during the development of the line. This may lead to the need of replacement of the already installed equipment.

Moreover, an optimal power according to the $OSNR_M$ criterion depends not only on parameters of the line but also on the parameter of the transponder ($OSNR_{BTB}$). Thus the change of transponder can lead to the need of re-calculation of the optimal power. In multi-channel DWDM systems parameters of transponders can vary for different channels (because transponders of various vendors can be used), and provision of optimal powers P_M in all channels simultaneously using a single EDFA is impossible.

Thus each method of optimization (using *BER* criterion and using $OSNR_M$ criterion) has its own benefits and drawbacks in a practical implementation. Optimization using the *BER* criterion allows building more cost-effective lines, and calculation of the optimal power in each span does not depend on parameters of other spans. But in this case the line does not have the highest possible resistance to possible degradations. Also the *BER* method does not enable achieving of a maximal reach of the line with OSNR margin required for commissioning, as will be shown below (Fig. 3).

In order to combine benefits of both methods and eliminate their drawbacks we have developed a new method of optimization called a “guaranteed OSNR margin” method.

5. The “guaranteed OSNR margin” method of optimization

During the commissioning of commercial fiber optic lines it is

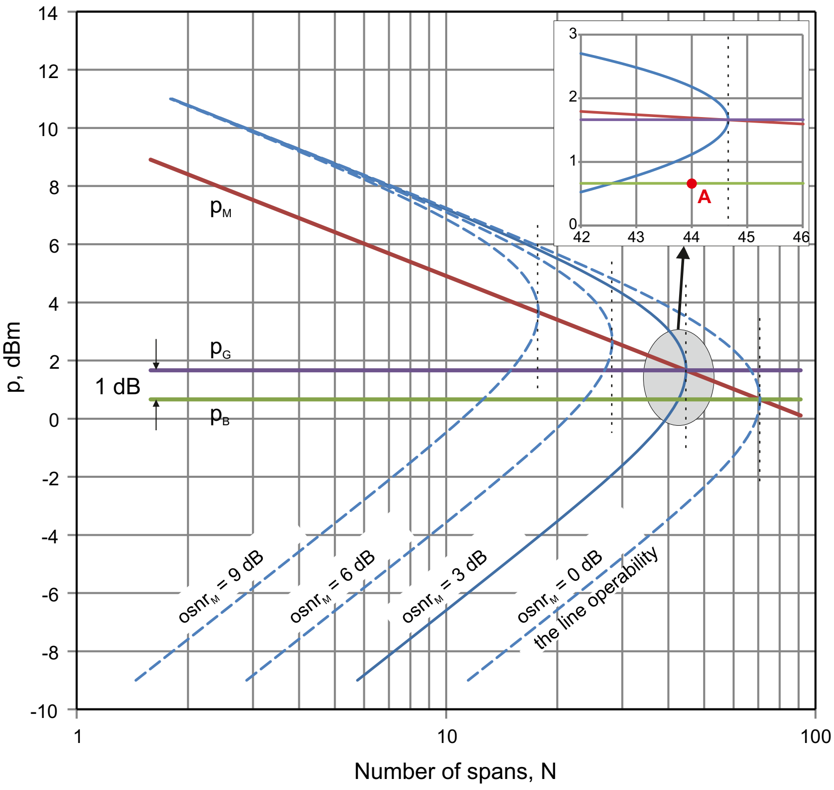

Fig. 3. Dependence of optimal powers p_M, p_B and p_G on the number of spans (for a line with equal spans).

Table 2
Comparison of different methods of optimization.

Method of optimization	$OSNR_M$	P_i
Maximization of $OSNR_M$	$2\left(\frac{\Psi}{3}\right)^{\frac{3}{2}}$	$\left(\frac{OSNR_M C_i}{2\eta_i}\right)^{\frac{1}{3}}$
Minimization of BER	$\frac{\Psi}{\sqrt[3]{2}} - \frac{1}{2}$	$\left(\frac{C_i}{2\eta_i}\right)^{\frac{1}{3}}$
Guaranteed $OSNR_M$ (with $K = 2$)	$\Psi - 1$	$\left(\frac{C_i}{\eta_i}\right)^{\frac{1}{3}}$
Guaranteed $OSNR_M$ with an arbitrary K	$\left(\frac{K}{2}\right)^{\frac{1}{3}}\Psi - \frac{K}{2}$	$\left(\frac{KC_i}{2\eta_i}\right)^{\frac{1}{3}}$

required to provide not only the line operability according to the formula (6), but some excess of $OSNR_R$ over $OSNR_L$. A usual requirement for commissioning is 2-fold excess (or 3 dB in logarithmic units):

$$OSNR_M > 2. \tag{20}$$

$$\frac{1}{OSNR_R} > 2\frac{1}{OSNR_L}.$$

$$2\frac{1}{OSNR_L} + \frac{1}{OSNR_{NL}} < \frac{1}{OSNR_{BTB}}. \tag{21}$$

Substituting into (21) the expressions (14) and (15), we obtain:

$$\sum_{n=1}^{N}\left(\frac{2C_n}{P_n} + \eta_n P_n^2\right) < \frac{1}{OSNR_{BTB}}. \tag{22}$$

The idea of the new method is to use for optimization not the criterion of operability of the line (8), but the criterion of commissioning of the line, for example, (22) if 2-times excess of $OSNR_R$ over $OSNR_L$ is needed for commissioning.

Let's find the minimum of the expression in the left part of the inequality (22) considering it as a function of P_n, $n = 1, \ldots, N$. The optimization is performed independently for each span, so we can find an optimal power for each span using the new method:

$$P_{G,n} = \left(\frac{C_n}{\eta_n}\right)^{1/3}. \tag{23}$$

In logarithmical units:

$$p_{G,n} = \frac{1}{3}\left(-58 + \alpha_n L_n + NF_n - 10\lg\eta_n\right). \tag{24}$$

The value of the function in this point is equal to $3\left(C_n^2\eta_n\right)^{1/3}$. Thus we can write a general criterion for commissioning of the line with N spans using the "guaranteed OSNR margin" method:

$$3\sum_{n=1}^{N}\left(C_n^2\eta_n\right)^{1/3} < \frac{1}{OSNR_{BTB}}. \tag{25}$$

A value of optimal power according to the "guaranteed OSNR margin" method is 1 dB greater than on the BER criterion (if we take a requirement of a two-fold excess of $OSNR_R$ over $OSNR_L$), Fig. 3.

The OSNR margin that is required for commissioning may depend on an average span length in the line. For example, for a line that consists of 50 km spans the required OSNR margin may only be 2 dB, whereas for a line that consists of 120 km spans the margin can be 4 dB. The proposed method can be easily generalized to include such cases.

In general form, the requirement for commissioning of the line can be written as:

$$OSNR_M > K. \tag{26}$$

In this case, we offer to optimize the line using the expression:

$$\sum_{n=1}^{N}\left(\frac{KC_n}{P_n} + \eta_n P_n^2\right) < \frac{1}{OSNR_{BTB}}, \tag{27}$$

where K can be regarded as an optical robustness coefficient. In previous discussion and below we take $K = 2$, but in general case one can set K to any value above 1 according to network requirements.

One can also use different K_i for different spans as a more sophisticated criterion of optimization; although this method does not guarantee any definite value of OSNR margin for the whole line.

To simplify the comparison of different methods, let's introduce a parameter Ψ:

$$\Psi \equiv \left(OSNR_{BTB}\sum_i\left(C_i^2\eta_i\right)^{\frac{1}{3}}\right)^{-1}. \tag{28}$$

The Ψ can be considered as a parameter of the quality of the line that takes into account three aspects of the line: parameters of ASE noise, nonlinear effects, and characteristics of a transponder. The Ψ is higher for better lines. Thus we can compare different lines using a single integral parameter.

Using the Ψ we can represent results of all methods in a simple form, see Table 2.

In case of the line optimization based on new method, an optimal power in each span depends only on parameters of this span (local optimization), as well as when the line is optimized using the BER criterion. All spans may have different lengths, attenuations, noise factors of amplifiers and coefficients of nonlinearity. Thus it is not necessary to recalculate optimal power values during the development of the line when new spans are added.

At the same time, the optimization using the new method guarantees that calculated values of optimal powers will allow commissioning of the line (if the line can be commissioned in principle). Indeed, if the condition (25) is satisfied then the condition (20) is also satisfied. In case if the new method gives a set of power values that does not satisfy the condition (25) it means that the line cannot be brought into service for any set of power values (in contrast with the BER optimization).

Using the BER criterion for lines with lengths close to critical length it is possible to get a set of optimal power values $P_{B,n}$ that does not allow bringing the line into service, while for the same parameters of the line the range of values P_n exists that allows it. For example, see point A on the Fig. 3: a calculated value of P_B does not allow the commissioning ($OSNR_M < 2$) while higher values of P allow bringing into service ($OSNR_M > 2$) for the same parameters of the line.

An example of application of different methods of optimization of the line is shown on Fig. 4. We use real span lengths for a fiber optic telecommunication line Moscow–Nizhny Novgorod–Samara (Russia), Fig. 4b. Two stages of development of the line are considered: 5 spans to be commissioned at a first stage, and 6 more spans to be commissioned at a second stage.

Parameters of the line: attenuation of the fiber is 0.22 db/km, additional attenuation per span is 1 dB (allowance for connectors), EDFA noise factor is 5.5 dB, non-linearity coefficient η for one span is 4.5×10^{-4} mW^{-2} (80-channel DWDM system with 50 GHz spacing), $OSNR_{BTB}$ is 12.5 dB.

Optimal input powers for each span achieved by different methods are shown on Fig. 4a. Method of maximization of OSNR margin provides OSNR margin 6.71 dBm for 5 spans and 3.15 dBm

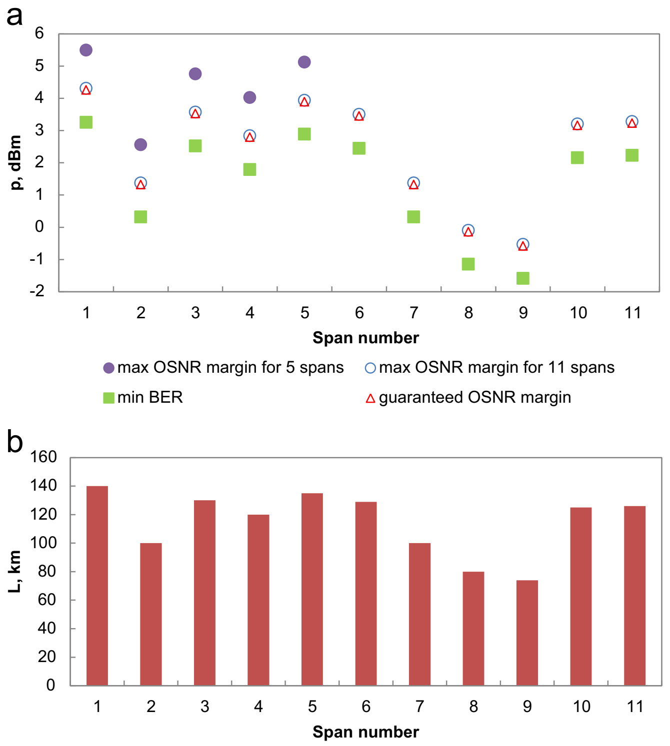

Fig. 4. (a) Dependence of optimal input powers on the number of span for different methods of optimization; (b) lengths of spans.

for 11 spans; optimal powers for first 5 spans are changed after the expansion of the line. Method of guaranteed OSNR margin provides OSNR margin 6.33 dBm for 5 spans and 3.15 for 11 spans (i.e. these two methods are practically coinciding for maximal possible lengths of the line). Method of minimization of BER provides OSNR margin 5.68 dBm for 5 spans and 2.86 dBm for 11 spans (i.e. it does not enable bringing the line into service at the second stage).

6. Conclusions

In this article, we discussed the main issues that should be taken into account during designing high-bit rate optical transmission systems impaired by Kerr non-linear effects. It was shown that reliable engineering rules are necessary to be developed in order to deal efficiently with the complexity of the modern coherent systems. Experimentally proved phenomenological models and practical engineering rules enable construction of optical networks one step beyond the capacities of today's purely analytical reasoning.

More particularly, we focused on a development of a general method of optimization of fiber optic lines that enables engineer to achieve maximal reach of the designed line and at the same time to guarantee the OSNR margin that is required for successful commissioning of the commercial fiber optic lines. Analytical expressions of the optimum fiber input power distribution and of the system reach were derived, and can be used for designing coherent optical networks with optimal performance.

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