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Correlation of nonlinear noises from different spans in 100 Gb/s multi-span fiber optic lines

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ABSTRACT

The accumulation of nonlinear noise in multi-span communication lines was investigated by numerical modeling and experimentally for different values of accumulated dispersion at input of each span. One coherent 100G channel was investigated (wavelength 1549.32 nm, DWDM channel C35). It has been established that interaction of nonlinear noises from two different spans can be described by a correlation function that depends only on values of input dispersion for these spans. It confirms the idea that the nonlinear noise in a fiber optic line is formed mainly due to signal to signal interaction, and the influence of the signal to noise interaction can be neglected. The shape of correlation function was investigated by numerical modeling and experimentally, and its simple approximation was offered. The nonlinear noise in any multi-span line with arbitrary dispersion plan can be calculated based on the investigated correlation function for two spans. It was shown that in a compensated line the offered theoretical model based on correlation function corresponds well to simpler theoretical model based on superlinear dependence of total noise on number of spans.

1. Introduction

Uncompensated fiber optic communication lines with 100G and higher rates become dominating in backbone data transmission networks. Many recent works were devoted to investigation of such lines [1–26]. At the same time, there are still a lot of exploited lines with coherent (100G and higher) and non-coherent channels (10G, 2.5G) transmitted simultaneously. In such heterogeneous lines, dispersion compensation units (DCUs) are used to implement various dispersion plans with full or partial compensation of dispersion.

The most sophisticated task in designing coherent communication system is a calculation of nonlinear noise for the multi-span line. Although there is a model to calculate such noises for uncompensated lines (based on superlinear addition of noises from different spans), there is still no universal model for calculation of nonlinear noises that can be used for both compensated and uncompensated multi-span lines.

The aim of our work is to create a model for calculation of nonlinear noise in a multi-span line that can be used for any arbitrary values of input dispersions in each span, covering both compensated and uncompensated lines as well as all intermediate cases.

In practice, the most common task is adding of one coherent 100G channel in an existing compensated DWDM-system with 10G channels. So we will focus on investigation of nonlinearity in a single 100G channel.

The concept of nonlinear noise was first introduced in early 1990s in the original paper [27]. 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 [14]. Turning from the absolute values of noises to signal-to-noise ratios, this formula can be written as follows:

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

The value of nonlinear noise in a span depends on a signal power P at the input on the span by a phenomenological rule $P_{NL} = \eta P^3$, where η (*eta*) is a non-linearity coefficient. Coefficient η depends on span properties (length, attenuation, residual dispersion at the input of the span, configuration of other channels) and

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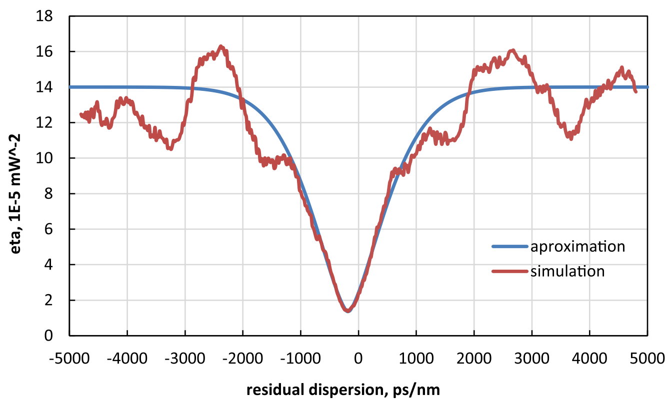

Fig. 1. Dependence of nonlinear noise in a single span on a value of residual dispersion at the input of the span (OptSim simulation and approximation).

does not depend on signal power, so we can write:

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

We can also define coefficient η for the whole multi-span line in the same way, if assume equal powers at inputs of all spans.

It was shown experimentally and theoretically in a number of recent works that this nonlinear noise can be described as a Gaussian noise [1,5–7,14–19]. Gaussian nature of the nonlinear interference (NLI) noise fields is conditioned by Gaussian distribution of the information sampled signal [15–18,26]. The Gaussian noise (GN) model of NLI noise is attractive for practical use because it enables elementary system optimization rules based on the signal-to-noise-ratio [4,10,24,25]. Phenomenological model of a multi-span line based on the presented concept of nonlinear noise is described in details in [4].

Dependence of nonlinear noise in a single span on a value of residual dispersion at the input of the span was investigated in [19] and [3]. The article [19] reports permanent increase of nonlinear noise power generated in one span with the increase of residual dispersion at the input of the span. In contrast with [19], our research [3] has shown that the nonlinear noise power generated in one span is practically independent on the amount of dispersion accumulated before this span for the values of residual dispersion more than 2 ns/nm, Fig. 1.

Dependence of η on d for a single span can be approximated with the expression:

$$\eta(d) = \eta_0\left(1 - \exp\left(-\mu - \left|\frac{d - d_0}{\rho d_0}\right|^{\frac{3}{2}}\right)\right) \tag{3}$$

where the values of coefficients are presented in Table 1:

The accumulation of nonlinear noise in a multi-span line without dispersion compensation was investigated in several recent works [3,11,19]. Experimental and theoretical researches have shown that the nonlinear noise power in a long multi-span line increases with the number of spans a bit faster than just a linear addition of noises from different spans. Power of exponent in this superlinear dependence slightly varies in different researches: 1.37 [19], 1.24 [11], 1.15 [3].

Table 1
Coefficients of the expression (3) for a single span.

Parameter	Value	Dimension
η_0	14	10^{-5} mW^{-2}
μ	0.1	–
ρ	5	–
d_0	−180	ps/nm

In our previous work [3] we supposed that the possible reason for superlinear dependence of nonlinear noise power on the communication line length is a correlation of noises that are generated in different spans. Current work is aimed to further research of this hypothesis. We attempt to build the correlation function that describes interaction of nonlinear noises from two different spans with arbitrary values of residual dispersions at inputs.

2. Numerical modeling

Numerical modeling was performed in OptSim software for a single channel 100G in a multi-span line with equal spans. Each model span consists of a SSMF fiber segment, a DCF fiber segment, and an EDFA, Fig. 2.

Parameters of the model span are shown in Table 2.

All spans are equal. This gives a dispersion plan with a uniform increase of accumulated dispersion. Additional dispersion from each span can be calculated as:

$$d_s = DL + D_c L_c \tag{4}$$

Residual dispersion at the input of a span depends on the number of span i as:

$$d_i = (i - 1)d_s \tag{5}$$

When the length of compensating fiber equals to 17 km, the dispersion in each span is fully compensated. If the length of compensating fiber is less (or more) than 17 km, then the under- (or over-) compensation takes place. Using numerical simulation and formulas (1) and (2), we can plot the dependence of nonlinearity of the line η (*eta*) on additional dispersion in each span d_s. Results of simulation for 2-span, 5-span and 8-span lines are shown on Fig. 3.

Let's try to describe the observed behavior of multi-span lines taking into account the known behavior of a single span (3). The S-shaped dependence of η from d_s is more evident in 5-span and 8-span lines.

2.1. Linear model

The simplest model is the direct addition of nonlinear noises from different spans:

$$\frac{1}{OSNR_{NL}} = \sum_i \frac{1}{OSNR_{NL,i}} \tag{6}$$

Results of modeling using formulas (6), (2) and (3) are shown on Fig. 4.

It is obvious that the simplest model of direct addition is not usable for multi-span lines. The supposed reason is the interaction of nonlinear noises from different spans.

2.2. Superlinear model

More advanced model is based on superlinear addition of noises from different spans:

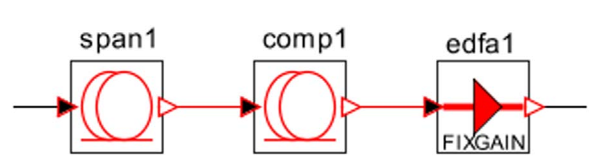

Fig. 2. Scheme of a span in a multi-span line, OptSim model.

Table 2
Parameters of the model span.

Parameter	Symbol	Value	Dimension
Fiber length	L	100	km
Fiber attenuation	α	0.2	dB/km
EDFA noise factor	NF	6	dB
Coefficient of nonlinearity of the fiber	γ	1.3	1/W/km
Dispersion of the fiber	D	17	ps/nm/km
Length of the compensating fiber	L_c	12–22	km
Dispersion of the compensating fiber	D_c	−100	ps/nm/km

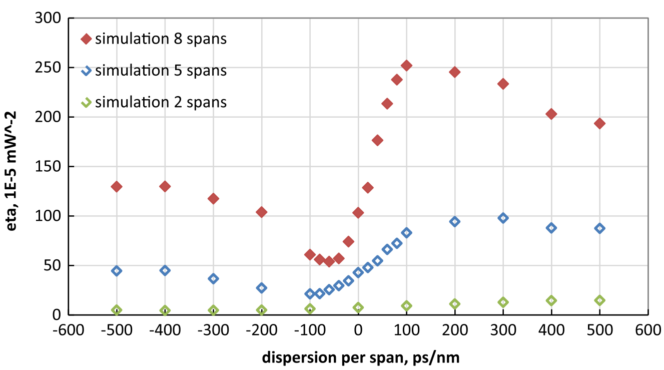

Fig. 3. Dependence of nonlinearity in multi-span lines on additional dispersion in each span (OptSim simulation, 100G channel).

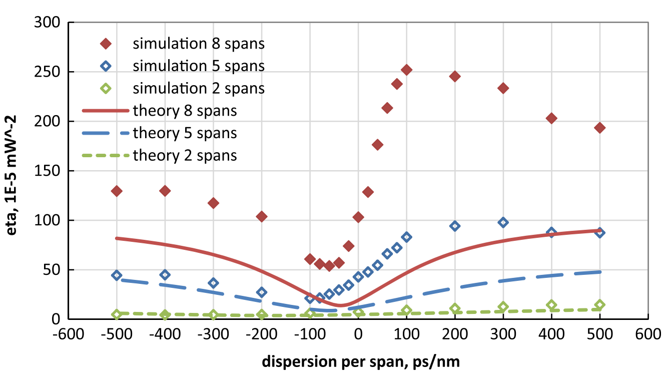

Fig. 4. An attempt of approximation of nonlinearity in multi-span lines using the simplest model of linear addition of nonlinear noises from different spans.

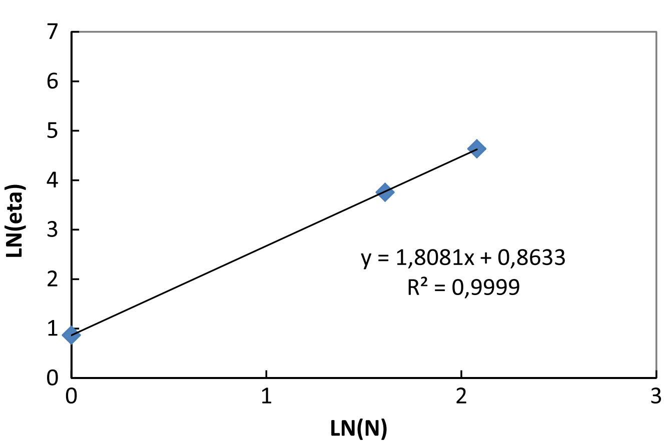

Fig. 5. Dependence of nonlinearity on number of spans (for equal spans with full compensation of dispersion in each span), OptSim modeling.

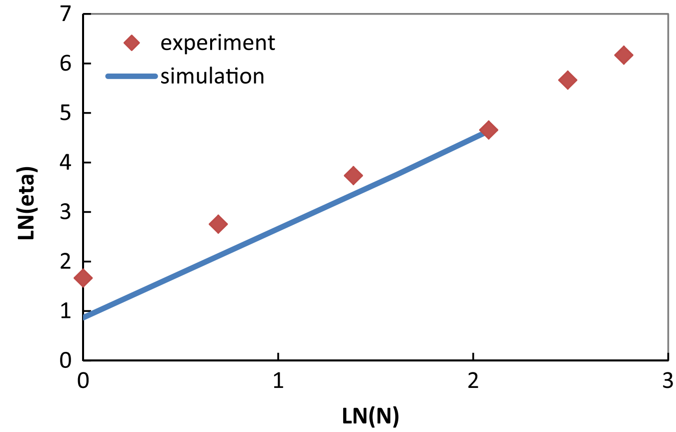

Fig. 6. Comparison of the modeling and experimental data.

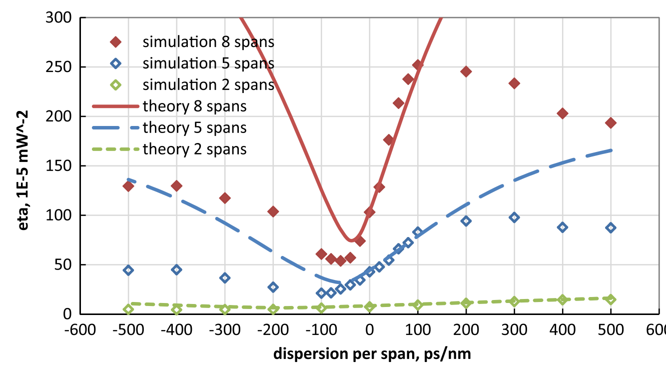

Fig. 7. An attempt of approximation of nonlinearity in multi-span lines using the model of superlinear addition of nonlinear noises from different spans.

$$\frac{1}{OSNR_{NL}} = \left(\sum_i \left(\frac{1}{OSNR_{NL,i}} \right)^{\frac{1}{1+\varepsilon}} \right)^{1+\varepsilon} \tag{7}$$

Parameter ε is in the range from 0 to 1. In case of equal spans the formula (7) gives the dependence of nonlinearity of the line η from number of spans N:

$$\eta \sim N^{1+\varepsilon} \tag{8}$$

When $d_s = 0$ all spans are equal and we can find ε by plotting dependence of η from N in double logarithmic coordinates. Fig. 5 shows results for $N = 1$, 5, 8 and their approximation by a straight line. Slope of the line gives us the value of $\varepsilon = 0.81$.

Fig. 6 shows a comparison of the approximation based on numerical modeling (line) and our experimental data for multi-span lines with equal spans (dots).

Let's try to use superlinear model for description of nonlinearity in multi-span lines. Fig. 7 shows results of our simulation of nonlinearity in 5-span and 8-span lines and their comparison with calculations based on formulas (7), (2) and (3) with $\varepsilon = 0.81$.

We can conclude that the superlinear model with $\varepsilon \approx 0.8$ can be used for calculation of nonlinearity in fiber optic lines with the full compensation of dispersion or slight under-compensation (so that additional dispersion in each span equals approximately 0 … 100 ps/nm). But the superlinear model fails to describe the general behavior of the nonlinearity in the multi-span lines.

2.3. Correlation model

In order to describe interaction of nonlinear noises from different spans, let's suppose that noises from each two spans are

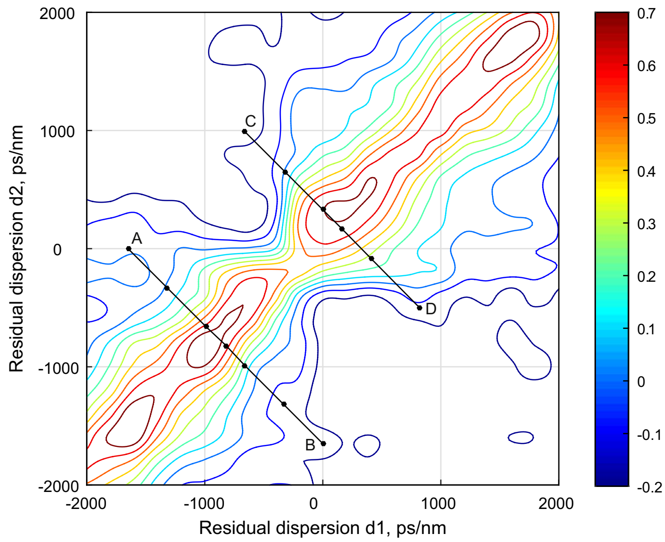

Fig. 8. Numerical simulation of the correlation function (OptSim). AB and CD are cross-sections measured experimentally (see below).

Table 3
Coefficients of the correlation function.

Parameter	Value	Dimension
a_1	0.6	–
a_2	150	ps/nm
a_3	500	ps/nm

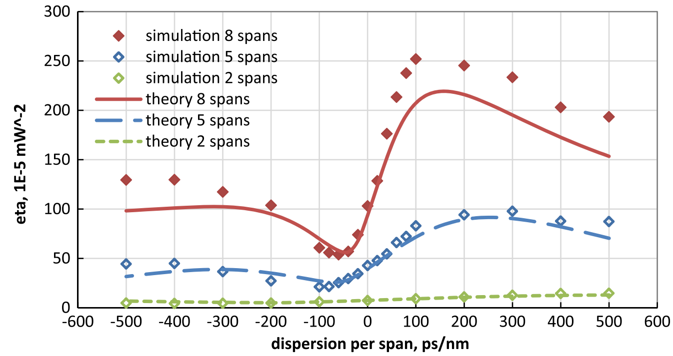

Fig. 10. An attempt of approximation of nonlinearity in multi-span lines using the model of correlation of noises from different spans.

correlated:

$$\frac{1}{OSNR_{NL}} = \sum_i \frac{1}{OSNR_{NL,i}} + 2\sum_{j>i} \sigma_{ij}\sqrt{\frac{1}{OSNR_{NL,i}}\frac{1}{OSNR_{NL,j}}} \tag{9}$$

If input powers in all spans are equal and the formula (2) is executed then the formula (9) can be rewritten as:

$$\eta = \sum_i \eta_i + 2\sum_{i<j} \sigma_{ij}\sqrt{\eta_i\eta_j} \tag{10}$$

The coefficient σ_{ij} is a correlator of noises from spans i and j.

Let's suppose that σ_{ij} depends only on values of accumulated dispersion at the input of spans i and j (span i precedes span j, $i < j$), and does not depend on numbers i and j:

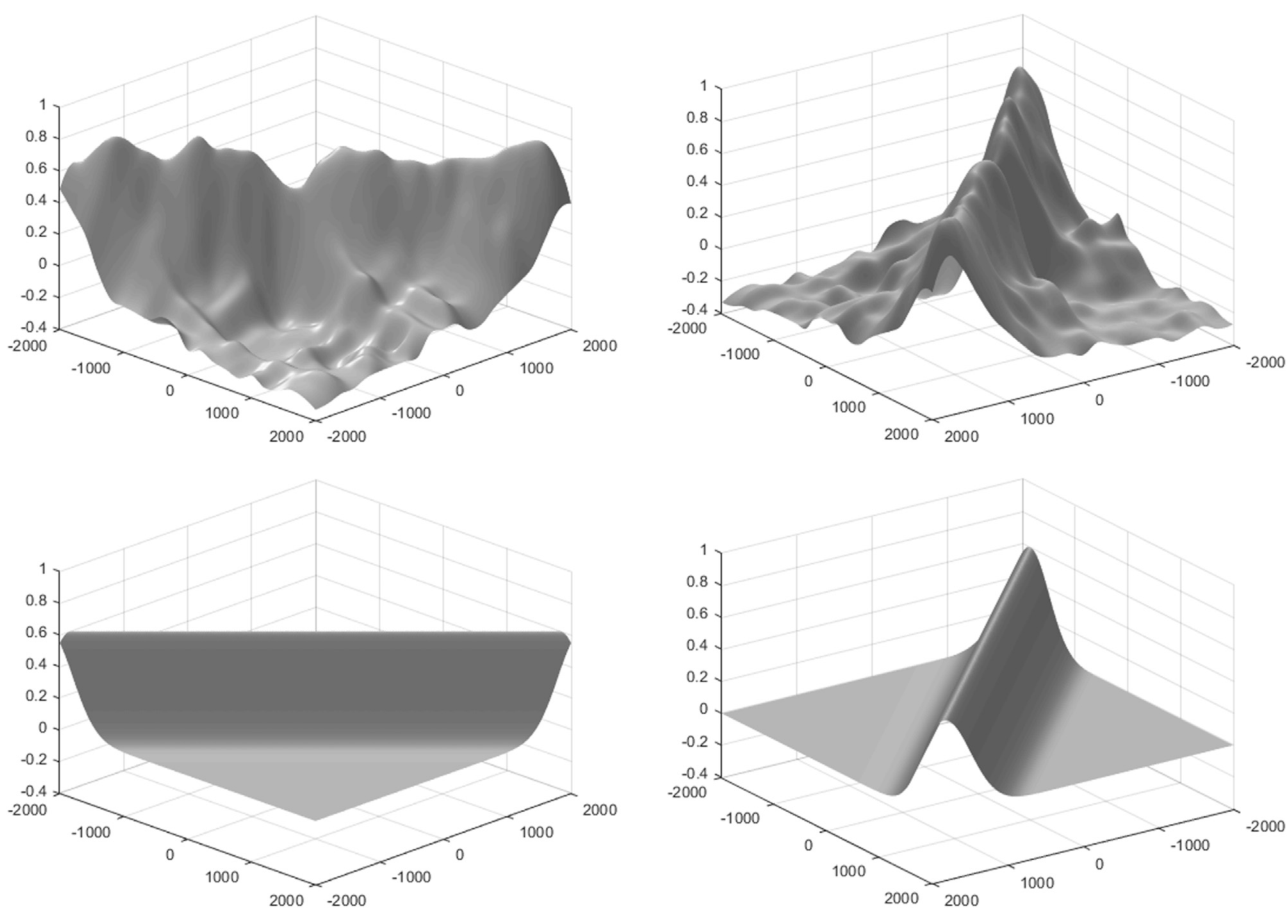

Fig. 9. Correlation function: OptSim modeling (top) and its simple approximation (bottom).

$$\sigma_{ij} = \sigma\left(d_i, d_j\right) \tag{11}$$

If so, we can investigate the correlation function for a 2-span line, and then use it for calculation of nonlinearity in arbitrary multi-span lines with any number of spans.

For example, for a 2-span line $\eta = \eta_1 + \eta_2 + 2\sigma\sqrt{\eta_1\eta_2}$, for a 3-span line $\eta = \eta_1 + \eta_2 + \eta_3 + 2\sigma\sqrt{\eta_1\eta_2} + 2\sigma\sqrt{\eta_1\eta_3} + 2\sigma\sqrt{\eta_2\eta_3}$, and so on.

For a 2-span line, σ can be calculated from numerical modeling or experimental data as:

$$\sigma = \frac{\eta - \eta_1 - \eta_2}{2\sqrt{\eta_1\eta_2}} \tag{12}$$

The 2-span line was modeled in OptSim. Results of numerical modeling of σ as a function of d_1 and d_2 (level curves) for a 2-span line are shown on Fig. 8.

The simulated correlation function can be approximated with the formula:

$$\sigma = a_1\exp\left(-\left(\frac{d_1 - d_2 + a_2}{a_3}\right)^2\right) \tag{13}$$

where values of coefficients are presented in the Table 3.

Fig. 9 shows a 3D-surface of the correlation function built by numerical simulation and its simple approximation with formula (13).

Note that we use the simplest approximation that precise enough for practical calculation and design of DWDM lines. It does not reflect all details of the simulated correlation function, including its asymmetry and the peculiarity in the region of small negative dispersion ("saddle"). This region (approx. 0 … −300 ps/nm on both axes) should be excluded from the scope of our correlation model because nonlinear distortions not yet formed here and cannot be treated as a noise (GN-model in general does not work here). Also our simple approximation does not go to negative values (while numerical simulation does show negative correlation in some regions).

Let's use the described correlation model for description of nonlinearity in simulated multi-span lines. Fig. 10 shows results of our simulation of nonlinearity in 5-span and 8-span lines and their comparison with calculations based on formulas (13), (10) and (3).

The correlation model provides the required S-shaped dependence of η from d_s for 5-span and 8-span lines. Moreover, calculated values of nonlinearity correspond well with results of numerical simulation for all investigated range of additional dispersions per span (the accuracy is enough for practical use). So we can conclude that the correlation model describes the behavior of simulated multi-span lines more adequately than the superlinear model.

To check the offered correlation model experimentally, we have performed an experimental research that is described below.

3. Experimental setup

Experimental assemblies with 2 and 5 spans are schematically shown on Figs. 11 and 12. Each span consists of 100 km of SSMF fiber (G.652) preceded by a segment of DCF or SSMF fiber (named "DCU" on the figure). These DCUs are used to create necessary negative or positive residual dispersion at inputs of spans. EDFAs are used as shown on the scheme to set necessary signal power levels.

In the 2-span line, signal powers at inputs of spans are measured by optical spectrum analyzers (OSA1 and OSA2), Fig. 11. At the output of the line, a little part of the emission is sent to an optical spectrum analyzer (OSA3) using the optical coupler (splitter) to measure $OSNR_L$. An additional noise can be injected in the line using an amplified spontaneous emission (ASE) source;

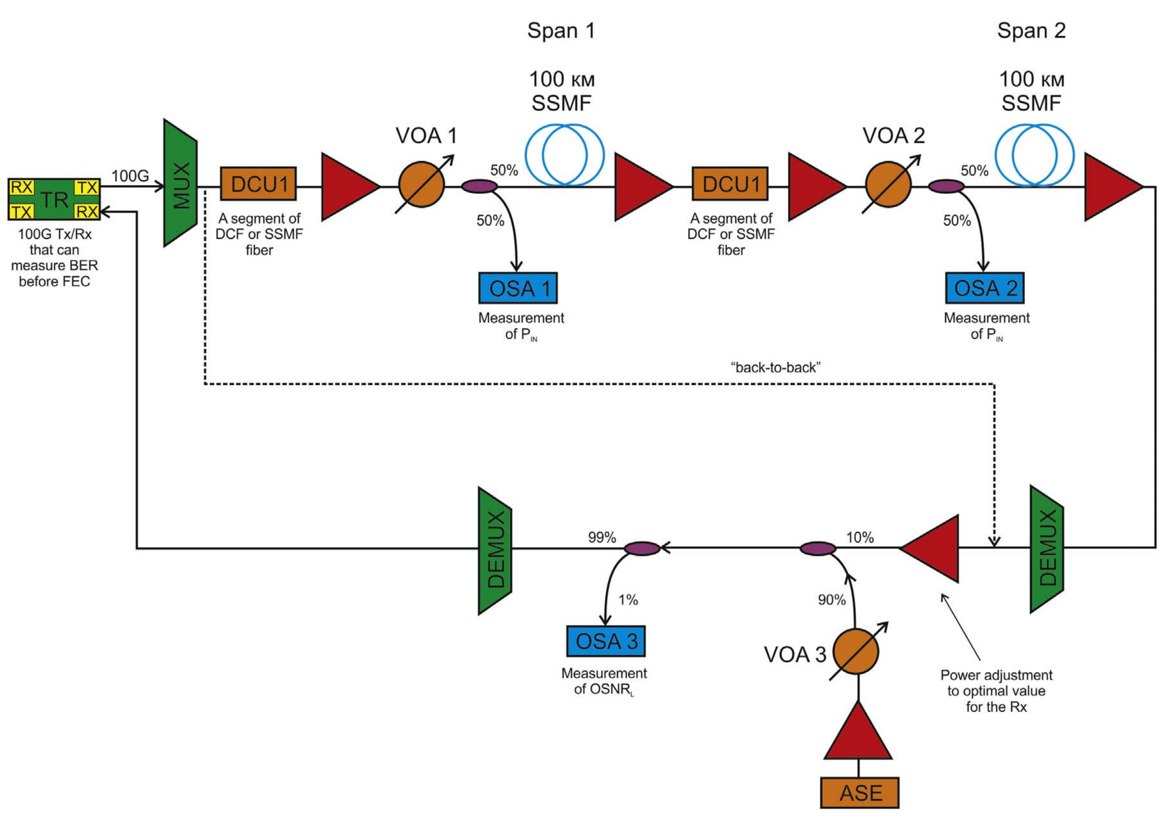

Fig. 11. Experimental setup, 2-span line. DCU – dispersion compensator unit (segment of DCF fiber for adding negative dispersion or segment of SSMF fiber for adding positive dispersion); TR – transponder with a function of measurement of BER before FEC.

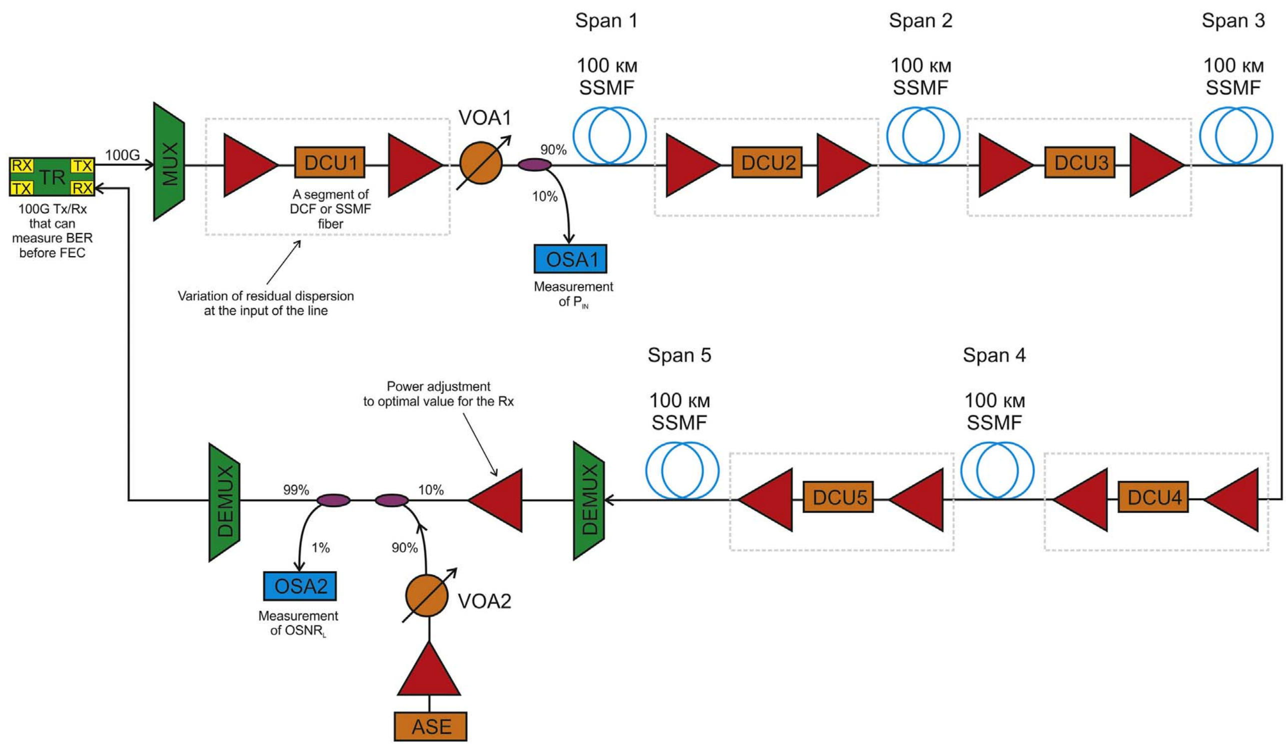

Fig. 12. Experimental setup, 5-span line. DCU – dispersion compensator unit (segment of DCF fiber for adding negative dispersion or segment of SSMF fiber for adding positive dispersion); TR – transponder with a function of measurement of BER before FEC.

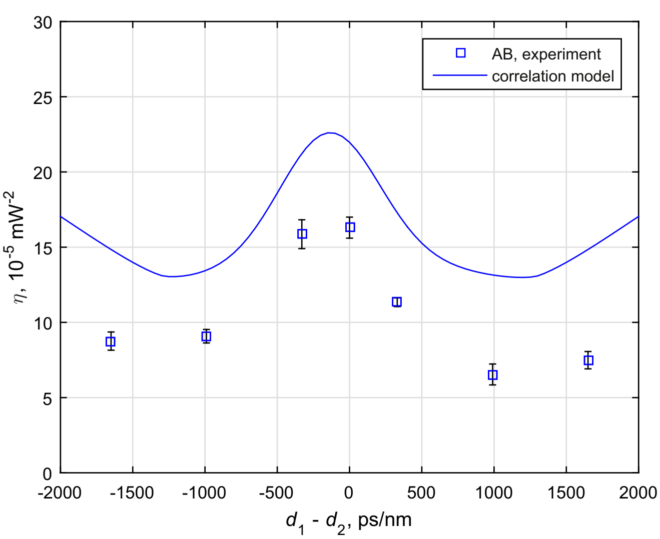

Fig. 13. Experimental measurement of nonlinearity in a 2-span line depending on input dispersions (cross-section AB on Fig. 8) and its comparison with theoretical calculations based on simple approximation of correlation function (13) and formulas (10) and (3).

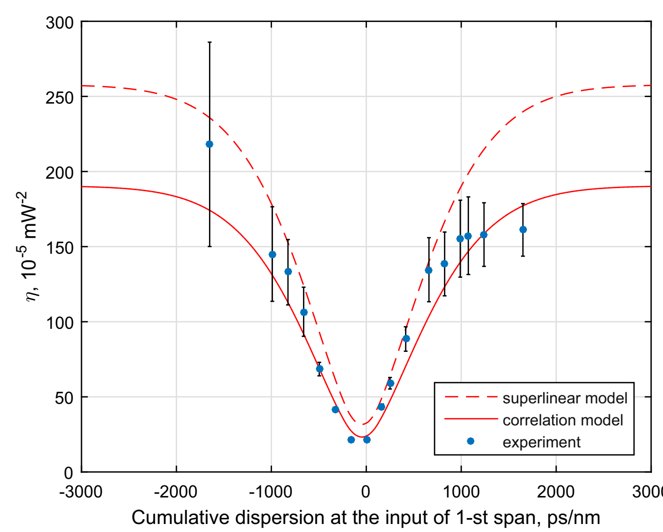

Fig. 14. Experimental measurement of nonlinearity in a 5-span line depending on input dispersion at the 1-st span (markers) and its comparison with theoretical calculations based on simple approximation of correlation function (13).

the noise level can be tuned using a variable optical attenuator (VOA 3). This part of scheme was used to measure waterfall curve of the transponder (dependence of BER before FEC on $OSNR_{BER}$ in a "back-to-back" scheme).

An optical transmitter converts an electrical signal into an optical signal with NRZ PDM-QPSK modulation format (Non-Return-to-Zero Polarization-division Multiplexed Quadrature Phase Shift Keying). We used commercially available transponder based on full C-band tunable external cavity lasers (ECL) with approximately 100 kHz width of the emission band. The symbol rate is 30 GBaud and the bit rate is 120 Gbit/s (each QPSK symbol bears 2 bits, and two QPSK symbols are transmitted simultaneously using two polarizations). The transponder contains an intrinsic pseudorandom signal generator and a tool for measurement of bit error ratio (BER) before forward error correction (FEC). A more detailed description of the transmitter can be found in [28–30]. One 100G channel was transmitted at wavelength 1549.32nm (DWDM channel C35).

In a 2-span line, we measured both η in each span and η of the whole line. In a 5-span line, we measured only η of the whole line.

To calculate the η in a span (in a 2-span line), the following algorithm was used. Signal power at the input of the investigated span P_{in} was set to values providing BER level in the region of $10^{-3}...10^{-5}$ (approx. 8...16 dBm, depending on residual dispersion). Signal power at the input of the other span was set to 5 dBm

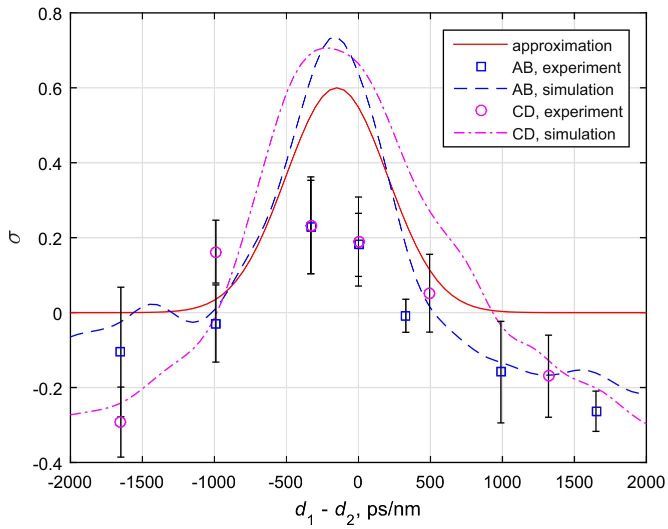

Fig. 15. Experimental measurement of correlation function σ along cross-sections AB (7 points) and CD (6 points), see Fig. 8, and corresponding simulated profiles. Approximation per formula (13) is also shown.

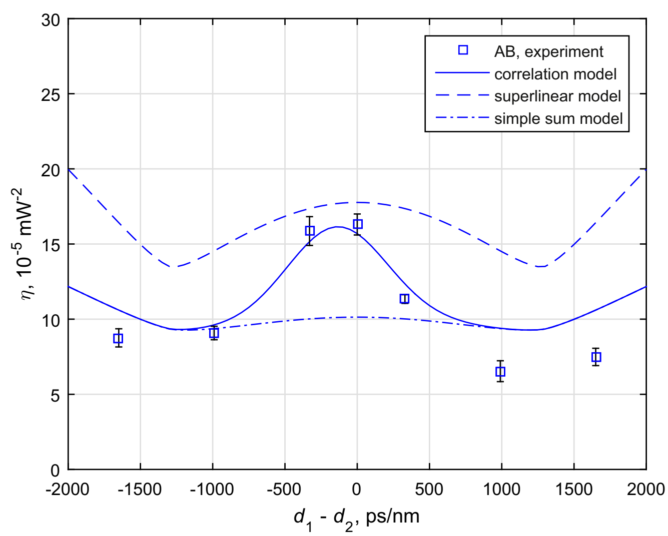

Fig. 16. Experimental measurement of nonlinearity in a 2-span line depending on input dispersions (cross-section AB on Fig. 8) and its comparison with theoretical calculations based on formulas (13), (10) and (3) with corrected parameter η_0.

(linear mode). Dependence of BER before FEC on P_{in} in the investigated span was measured, then formulas (1) and (2) and waterfall curve of transponder were used to plot the dependence of $1/OSNR_{NL}$ on P_{in}^2. The slope of the curve gives η.

To calculate η for the whole line (in 2-span and 5-span lines), signal powers at inputs of all spans were set equal, and then the signal power was varied as described above.

4. Experimental results

In the 2-span line, a pairs of dispersions of DCU1 and DCU2 were chosen in such a way to make two cross-sections of the main "ridge" of the correlation function; AB and CD (see Fig. 8). The measured shape of dependence of η from $d_1 - d_2$ for the 2-span line corresponds well to a theoretical prediction based on correlation model (13), (10) and (3), although absolute measured values are less than theoretical ones, Fig. 13. Possible reasons of inconsistency are discussed in the next chapter.

In the 5-span line, dispersions of DCU2…5 were chosen in such a way to create a dispersion plan with small over-compensation (approximately 50 ps/nm per span). Dispersion of DCU1 was varied in a range from −1700 to 1700 ps/nm. A measured nonlinearity in 5-span line was in good accordance with the theory, Fig. 14.

In the 2-span line, we also tried to calculate σ based on measured η in each span and η of the whole line using the formula (12), Fig. 15. The experiment confirmed the simulated shape of correlation function, although maximal experimental values occurred to be smaller than simulated ones. Possible reasons of inconsistency are discussed in the next chapter. The experiment also confirmed negative correlation in areas with large $d_1 - d_2$ (as well as in the OptSim simulation).

5. Discussion of the experiment

Inconsistency on Fig. 13 can be explained if we take into account the fact that the parameters of approximation (3), including the parameter η_0, were calibrated using experimental results for multi-span uncompensated lines (up to 20 spans). Nonlinearity in few-span lines is not as matured as in multi-span lines and its behavior is unstable. For example, if we use $\eta_0 = 10$ for a 2-span line, the theory will be more consistent with the 2-span experiment, Fig. 16.

The inconsistency on Fig. 15 is probably explained by a non-stable behavior of nonlinearity in few-span lines and its masking with other effects. The nonlinearity in a single span is probably overestimated in our experiment because of additional nonlinear noise from the other span; this effect leads to under-estimation of the correlation. The improvement of the experimental technique would probably enable achieving better results.

We can conclude that the offered theoretical model based on correlation function was qualitatively proven by experimental researches. Interaction of each pair of spans in a multi-span line can be described by the correlation function $\sigma(d_1, d_2)$, and the nonlinearity in a multi-span line with arbitrary dispersion plan can be calculated based on this correlation function.

For few-span lines (for example, 2-span) the model over-estimates the nonlinearity. Although it is not a significant drawback for practical tasks of designing DWDM lines, the model can be easily re-calibrated for few-span lines to achieve better consistency with the experiment.

6. Achieving optimal performance of the line

For practical use, the formula (9) can be rewritten in more simple form.

Matrix σ_{ij} is defined for $i < j$. In order to simplify further mathematical calculations, we can extend the definition for $i > j$ based on symmetry condition: $\sigma_{ij} = \sigma_{ji}$. Let's also add values on the main diagonal: $\sigma_{ii} = 1$. Based on this extended correlation matrix, let's define the nonlinearity matrix H_{ij}:

$$H_{ij} = \sigma_{ij}\sqrt{\eta_i \eta_j} \tag{14}$$

For arbitrary values of span input powers the nonlinear noise can be calculated using the following power quadric form:

$$\frac{1}{OSNR_{NL}} = \sum_i \eta_i P_i^2 + \sum_{i \neq j} \sigma_{ij}\sqrt{\eta_i \eta_j} P_i P_j = \sum_{ij} H_{ij} P_i P_j \tag{15}$$

The formula (15) can be used for calculation of optimal input powers in spans of a multi-span line using different methods of optimization [4].

7. Conclusions

Computer simulations of 2-, 5- and 8-span lines have shown that the nonlinearity in a multi-span line can be described using a model of correlation of noises from different spans. In contrast with the superlinear model that requires different values of parameter ε for designing of different types of lines (and cannot predict a nonlinearity in a line with an arbitrary partial compensation), the offered model based on the correlation function can be used for calculation of nonlinear noises in multi-span lines with full or partial dispersion compensation for a wide range of residual dispersions.

The correlation function was investigated by numerical simulation and experimentally, and its simple approximation was offered. The nonlinearity in 2- and 5-span lines was experimentally measured and compared with the offered model. Experimental research proved the shape of the correlation function, although its maximal experimental values in the 2-span line occurred to be smaller than the numerical simulation. The discrepancy between theory and experiment in the 2-span line is probably described by a non-stable behavior of nonlinearity in few-span lines. For a 5-span line, consistency between theory and experiment is much better.

Both the numerical simulation and experimental research of correlation function revealed negative correlation of noises for some combinations of input dispersions (value of correlation function can be as low as -0.3). That means that nonlinear noises from different spans in multi-span line can compensate each other. This fact can be used in further researches and development of methods for compensation of nonlinear distortions in communication lines.

A correlation of nonlinear noises in communication lines with other formats of modulation should also be investigated in further researches.

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