Unifying theory of compensation techniques for intrachannel nonlinear effects

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Abstract: We show a new graphical method to identify and create configurations yielding to nonlinearity compensation in a fiber transmission system. Method validity is shown with regards to different link configurations and different compensation techniques. It is demonstrated that a unifying principle can always be applied, because only one physical effect is involved, even if different practical arrangements are proposed. Disclosed method allows gaining physical insight and can be applied to derive new compensation techniques; two examples of configurations derived using the proposed technique are also reported.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems; (190.4370) Nonlinear optics, fibers; (190.5040) Phase conjugation; (190.3270) Kerr effect.

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1. Introduction

Intrachannel nonlinear effects (INLE), due to the nonlinear interaction between overlapped pulses, are the main transmission impairment in high bit-rate (40 Gb/s or more) systems and their compensation is thus a primary concern for systems design [1]-[2]. Recently several different solutions have been proposed to reduce INLE impact on pulse transmission, but each of them is related to a specific link configuration, and thus misses of general validity.

In this paper a new, graphical method to identify system architectures producing INLE compensation is disclosed. Proposed approach has broad validity, since it allows considering any kind of amplification structure (lumped, distributed or hybrid), dispersion map (resonant, not-resonant, tedonic), fiber type (standard, dispersion compensating or non-zero dispersion-shifted) and modulation format (RZ or NRZ). Moreover this technique can take into account implementation constraints or non-ideal system configurations (like irregular amplifier spacing or not periodic dispersion-maps and power-profiles), difficult to be mathematically analyzed. In section 3 proposed approach is used to show that already known compensation techniques, based on optical phase conjugation [3]-[8] or employing dedicated dispersion maps [9]-[12], can be reviewed as different implementations of a single principle. Finally in section 4 two examples of link configurations producing nonlinearity compensation, and derived by proposed method, are reported and verified by numerical simulations.

2. Mid Span Spectral Inversion and Graphical Approach

Mid Span Spectral Inversion (MSSI) states that it is possible to compensate nonlinear effects completely, by placing an Optical Phase Conjugator (OPC) in the middle of a system that presents a symmetrical distribution of both dispersive and nonlinear effects. If this condition is satisfied the pulse evolution after the OPC is symmetric to that experienced before the OPC and thus all the distortions caused by nonlinearity, and odd-order dispersion, can be compensated. This happens because the nonlinearity produced on a pulse is perfectly compensated by that produced on its “conjugated copy”, an exact copy of the original pulse spectrally-inverted and with an opposite value of accumulated dispersion.

In the particular situation of high bit-rate transmission systems, the nonlinear distortion can be generally modeled as a perturbation to the dominant dispersive effects. Thus pulse changes are mainly due to temporal broadening (or narrowing), more than to spectral modifications. It is important to underline that this allows mitigating the nonlinear effect produced on a pulse by the nonlinearity produced on its temporally-inverted (but not spectrally-inverted) copy, because the spectral modifications of pulses are, at a first order approximation, generally negligible. This requirement on the temporally-inverted pulses can be viewed as a graphical-symmetry condition, by reporting on a diagram the value of the optical power as a function of the dispersion accumulated by pulses during propagation (in the following PADD: Power - Accumulated Dispersion Diagram). Nonlinearity compensation can be achieved, using this graph, when two regions of “nonlinear propagation” are obtained for symmetrical values of pulse’s accumulated dispersion, because the previously found condition (generating nonlinear effect on temporally-inverted pulses) is then satisfied.

Considering, as an example, a transmission system composed by two spans with a symmetrical power profile the optimum OPC position, according to MSSI theory, is in the middle of the link. In Fig. 1(left) the curve of optical power and pulse’s accumulated dispersion, along the ideal link, are reported. Combining these curves the PADD, Fig. 1(right), related to this configuration can be derived: positioning the OPC in the middle of the link makes the nonlinear regions, defined as those where $P>P_0/e$ (being P_0 the optical input power), to be symmetrically positioned with respect to the zero of accumulated dispersion. In the picture the four nonlinear regions (A, B, C, D) are those corresponding to the grey areas

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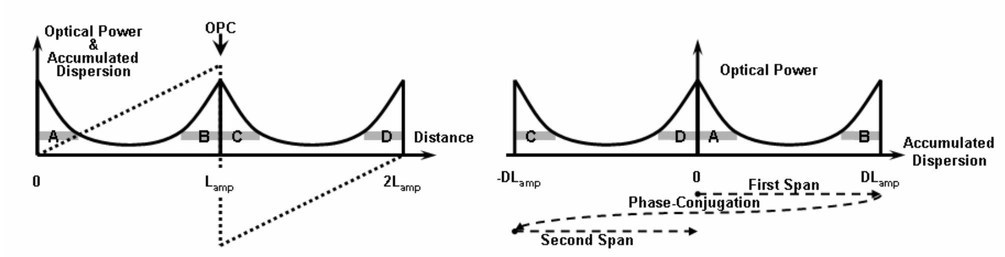

Fig. 1. Left: power and accumulated dispersion (solid and dotted line) required for MSSI. Right: derived PADD shows the perfectly symmetric distribution of nonlinear regions with respect to the zero of accumulated dispersion; DL_{amp} is the dispersion accumulated by signal during propagation on one span. The nonlinear (grey) regions A and B are symmetrical to regions D and C respectively.

In a general situation nonlinearity will be completely compensated if two conditions are satisfied: the entire power profile curve is symmetrical and pulses are both temporally and spectrally inverted; anyway, even if both these conditions are not verified, but a substantial symmetry of highly nonlinear regions is present, a partial nonlinearity compensation will be obtained. It is worth noting that this graphical approach is, in principle, less effective than the MSSI (no "perfect compensation" is guaranteed), but it's more viable, because it doesn't require unpractical constraints on power profiles, or the use of nonlinear devices like the optical phase conjugator (OPC). Moreover this approach may be viewed as a generalized version of the MSSI: if the system symmetries required for MSSI are satisfied the same result is obtained applying both techniques.

3. Analysis of Known Techniques

In a realistic link, like that illustrated in Fig. 2, MSSI can't be applied, because the nonlinearity distribution, in a typical optical system, is strongly asymmetrical. Applying the graphical approach a well defined OPC position, creating a symmetrical distribution of nonlinear regions in the PADD, can be found. This position, obtained by simple graphical considerations, is exactly coincident with the one that in [8] has been mathematically demonstrated to minimize pulse distortion.

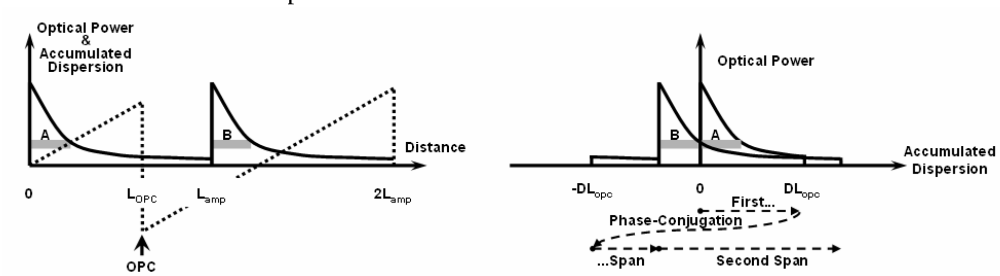

Fig. 2. Left: evolution of power (solid) and accumulated dispersion (dotted) considering the optimal, OPC position. Right: derived PADD highlights the symmetry of nonlinear regions

In a similar way any configuration, not only those reported in Fig. 1 and Fig. 2, producing INLE compensation in systems including an OPC can [4]-[7] be easily reviewed as a technique to produce symmetrical nonlinear regions.

Once observed that the PADD could describe several techniques for nonlinearity compensation by optical phase conjugation it is worth noticing that it can successfully explain also techniques for nonlinearity compensation in systems without an OPC. A well known solution to achieve nonlinearity mitigation is to carefully design link's dispersion map. Different maps optimizations reducing INLE have been proposed in literature, but always

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applied to particular configurations; thus no unifying explanation of their behaviour is known.

Three main classes of dispersion maps, depending on the amount of dispersion compensation inserted in each span, can be identified: no in-span compensation [9], partial span compensation [10], and complete span compensation [11]. It must be underlined that in the three situations three diverse solutions for nonlinearity compensation have been identified, all coincident with those that can be obtained analyzing the corresponding PADD. As an example let's consider the configuration including dispersion compensation only at the transmitter and receiver site. The mathematical analysis in [9] shows that the optimum distance to be pre-compensated, if lumped amplification is considered, is given by the following equation (where L_{amp} is the amplifier spacing, α the fiber losses and n the number of spans).

$$z_{prec,opt} = \frac{nL_{amp}}{2} - \frac{n(\alpha L_{amp} - 1) + (n-1)e^{-\alpha L_{amp}}}{2\alpha\left[n - (n-1)e^{-\alpha L_{amp}}\right]} \tag{1}$$

Being z_{msa} the position of mid-span amplifier and L_{eff} the effective length, defined in [14] as the length over which nonlinearity is significant, (1) can be reduced, considering long amplifier spacing ($\exp(-\alpha L_{amp}) \ll 1$) and an odd number of spans, to a form similar to that reported in [8]:

$$z_{prec,opt} = z_{msa} + \frac{L_{eff}}{2} - \frac{L_{amp}}{2} \tag{2}$$

This is noticeable because (2) and the results reported in [8] are identical, even if they have been obtained using two different approaches, and relate to two different link configurations: in [8] nonlinearity is compensated by means of optical phase conjugation, while in [9] nonlinearity is compensated by creating a proper dispersion map. This result thus underlines the strong connections between different techniques for nonlinearity compensation.

Analyzing the PADD of this link configuration (Fig. 3), the graphical effect of a pre-compensation is that of moving to the left the starting point of the diagram. If the extension of the nonlinear regions is L_{eff}, as in the case of lumped amplification systems, the optimum value of pre-compensation, found creating a symmetrical distribution of nonlinear regions with respect to the zero of accumulated dispersion, can be graphically determined to be:

$$z_{prec,opt} = \left\lceil \frac{n}{2} \right\rceil L_{amp} + \frac{L_{eff}}{2} \tag{3}$$

which matches solutions found in [8], where two equations have been provided in the case of an odd or even value of n, and include (1).

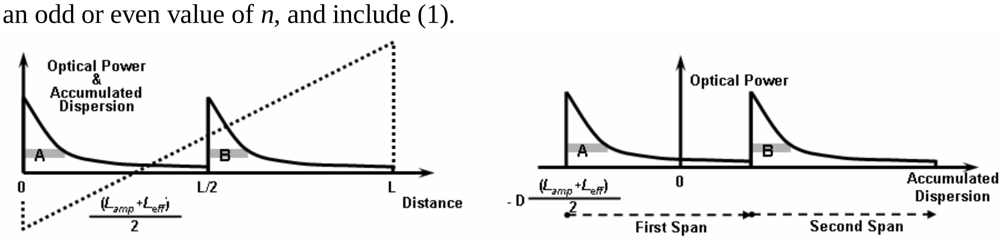

Fig. 3. Left: optimal positioning if n=2. Right: obtained PADD.

Similarly it can be demonstrated that all the configurations proposed in literature, and relating to different dispersion maps, act in the same way: making nonlinear region positions to be symmetrical in the PADD.

4. Configurations for Nonlinearity Compensation Derived by Graphical Analysis

Having demonstrated the ability of graphical approach to explain different techniques known in literature for nonlinearity compensation, it is interesting to report two link configurations (one based on OPC, the other on an appropriate dispersion map) producing nonlinearity compensation and identified using the PADD.

Considering first the opportunity to achieve nonlinearity compensation by using an OPC, two preliminary considerations have to be done: generally MSSI can't be applied because system power profile is strongly asymmetrical, and the "optimal OPC positioning" solution proposed in [8], useful for newly-designed transmission systems, seems not easily employable into embedded links, because an intra-span access point to fiber cable is required.

The PADD can thus be used to determine new system configurations satisfying the three following requirements: identified solutions must provide a sensible compensation of nonlinear effects, they must be applicable to real systems (where power profiles are generally asymmetrical, using EDFA), and no in-line access-point to fiber cable must be needed. These three conditions can be easily translated into three constraints regarding the PADD: nonlinear regions must be symmetrically placed, asymmetrical power profiles must be considered, and changes to system configuration can only be applied in a position corresponding to an amplifier site (not in the middle of the span between two amplifiers). Moreover to gain the maximum advantage from the presence of an OPC it is useful to focus on configurations employing one single OPC, and producing at the same time a substantial compensation of nonlinear effects as well as of chromatic dispersion.

Let's consider a system composed of four spans and including lumped amplification. With these conditions, several different approaches can be considered, depending on the kind (and number) of changes introduced along the system. The more interesting solution for practical implementation can be derived observing the PADD diagram of the original system configuration, shown in the following figure.

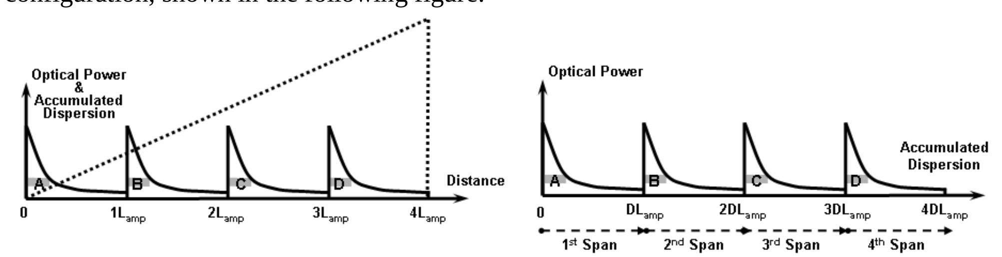

Fig. 4. Left: evolution, along the link, of optical power (solid) and pulse's accumulated dispersion (dotted). Right: The related PADD shows that nonlinear regions (areas A, B, C, D) are not symmetrical. In this example dispersion compensation is included only at the receiver.

Since four nonlinear regions are distributed along the system, the OPC has to be positioned between second and third nonlinear region; moreover the only access point to fiber cable available in that section of the system is given by the third amplification stage, at a distance $2L_{amp}$ from the transmitter. With these simple considerations the position of the OPC is then defined, but this positioning does not create a symmetrical distribution of nonlinear regions inside the PADD, and some system modification must thus be included.

The simplest way to achieve symmetry is to modify system dispersion map introducing an adequate displacement of nonlinear regions; practically this can be obtained adding, at the OPC site, an adequate dispersive element. According to the sign of introduced dispersion two different embodiments of this solution can be defined, as reported in Fig. 5.

If the dispersion introduced by added element has the same (or opposite) sign of the dispersion introduced by transmission fiber, it will be positioned after (or before) the OPC respectively; thus producing, in the PADD, an adequate translation of nonlinear regions. The absolute value of dispersion that has to be introduced ($D_{element}$ expressed as ps nm^{-1}) is, in both situations, coincident with the dispersion accumulated by pulses during propagation along last "linear region". Indicating the dispersion of transmission fiber with D_f (ps nm^{-1} km^{-1}), it is possible to observe that the value of $D_{element}$ producing the maximum compensation of nonlinear effects is defined by the following equation:

$$D_{element} = D_f \left(L_{amp} - L_{eff} \right) \tag{4}$$

The evolution of power and accumulated dispersion, together with derived PADDs, obtained considering both possible system implementations are reported in Fig. 5. It must be underlined that adding an appropriate dispersive element is a not critical operation: it can be easily obtained by adding an appropriate span of fiber, or a chirped Bragg grating.

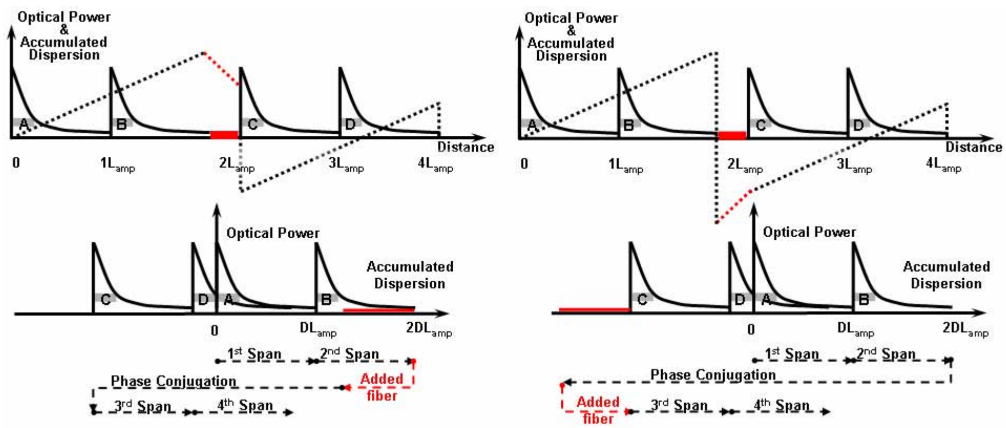

Fig. 5. PADD relatives to the two proposed configurations. In both cases nonlinear regions are symmetrical with respect to the axis of zero accumulated dispersion. Left: Added element (positioned upstream the OPC) has a dispersion sign opposite to that of transmission fiber. Right: The dispersion of fiber and of added element have the same sign, the element is thus placed downstream the OPC

To evaluate the effectiveness of this solution, numerical simulations have been performed on both Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) pulse propagation. To stress the impact of fiber nonlinear effects a 40Gb/s, single-channel transmission systems has been considered, and the average optical power input into spans has been set to 10dBm. Transmission performance has been measured using the Eye-Opening-Penalty (EOP) parameter, defined as the ratio between the maximum eye-opening measured at the transmitter and receiver site and expressed in decibel units. Moreover to demonstrate the absence of restriction on modulation format and fiber dispersion, four different implementations of a 18 x 100km link have been simulated, always considering the case of lumped (EDFA) amplification. In Table 1 the relevant parameters of considered fiber types are reported; please note that fiber F1 shows the typical parameters of a fiber complying with ITU recommendation G.652 (SMF), while F2 and F3 belong to the G.655 class (NZDSF).

Table 1. fiber parameters considered for simulations

Parameters	Unit	Fiber "F1"	Fiber "F2"	Fiber "F3"
Attenuation (α)	dB Km^{-1}	0.2	0.2	0.2
Dispersion (D)	ps nm^{-1} Km^{-1}	16.5	-4.6	4.6
Non-linearity (γ)	W^{-1} Km^{-1}	1.3	1.3	1.3

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Three systems implementations have been simulated using parameters of fibers F1 and F2; moreover RZ pulses, with T_{FWHM}=5ps (duty-cycle=0.2), have been considered to propagate on both the F1 and the F2 link, while NRZ pulses have been considered on the F2 link.

Dispersion compensation, at both the OPC site and the receiver site, has been supposed as ideal: no distortion effect or insertion loss has been included in simulations, thus making equivalent to analyze the two techniques reported in Fig. 5. In the following figure the obtained EOP, as a function of the dispersion compensated at the OPC site, is reported. To simplify the analysis, compensated dispersion has been indicated as the "compensated length" (L_{comp}):

$$L_{\text{comp.}} = \frac{D_{element}}{D_f} \tag{5}$$

Combining (4) and (5) the optimum value of L_{comp} is equivalent to (L_{amp}-L_{eff}); thus, with given data, it is approximately equal to 79km. It must be noted that considering the MSSI technique (compensated length equal to 0km in Fig. 6) a worst EOP is obtained; while through appropriate dispersion compensation an EOP of about 1dB, or lower, can be achieved.

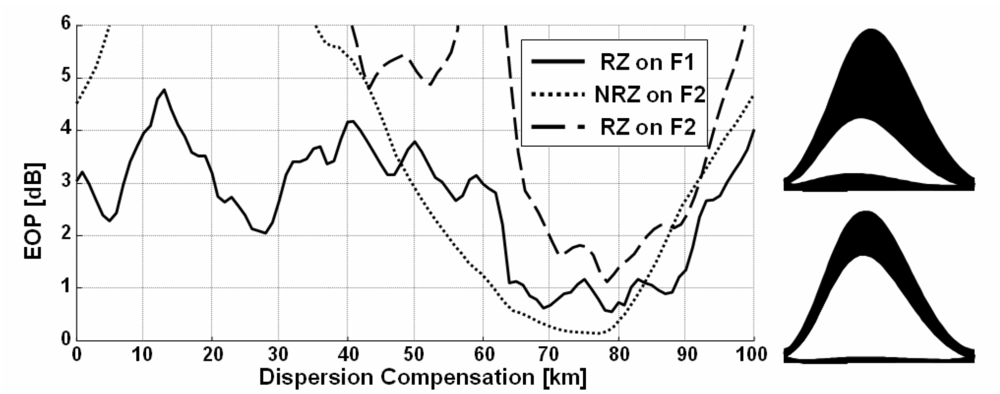

Fig. 6. Left: EOP as a function of dispersion compensated before the OPC.. Right: eye diagrams (RZ propagation on F1) when 0km and 79km (top and bottom) are compensated

The fourth system implementation considered was based on RZ pulse propagation on a system (18 x 100 km) of F3 fiber, to underline the absence of restriction on fiber dispersion. In Fig. 7 the evolution of the EOP and of the timing jitter accumulated by pulses during propagation on this system is reported. It can be seen that, by adding an appropriate Dispersion Compensating Module (DCM), a noticeable distortion compensation is produced while pulses propagate along the second half of the link.

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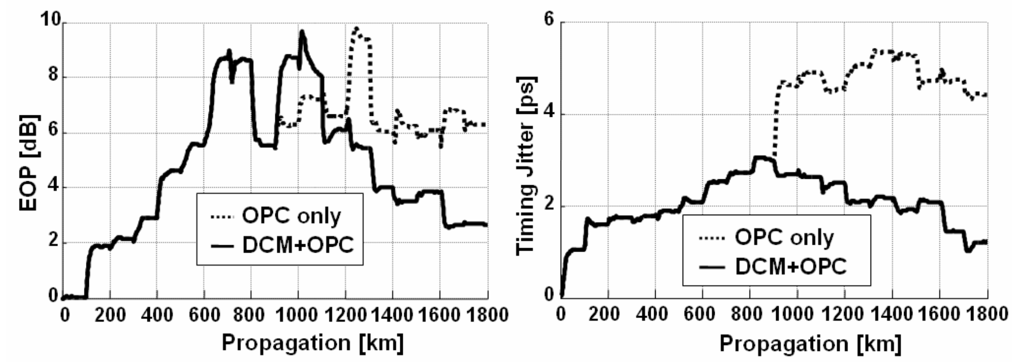

Fig. 7. The evolution of EOP (left) and timing jitter (right) is almost symmetrical if an appropriate DCM is added together with the OPC. Conversely both EOP and timing jitter grow in the second part of the link if no DCM is added, thus showing that the MSSI is not effective in this configuration.

In the second configuration proposed, the PADD can also be applied to identify nonlinearity compensation techniques based on the use of proper dispersion maps. To design a dispersion map suitable for practical implementation, and producing INLE compensation, two requirements must be satisfied: dispersion map must use low number of fiber types and "nonlinear regions" must be symmetrical in the PADD. Moreover, to allow simple path-reconfiguration, accumulated dispersion must be compensated on a span-by-span basis.

This can be achieved using a dispersion-map (Fig. 8) including two fibers in each span, and producing INLE compensation between nonlinear regions of subsequent spans; this solution, graphically identified in 2003 [13], has recently been mathematically demonstrated in [12].

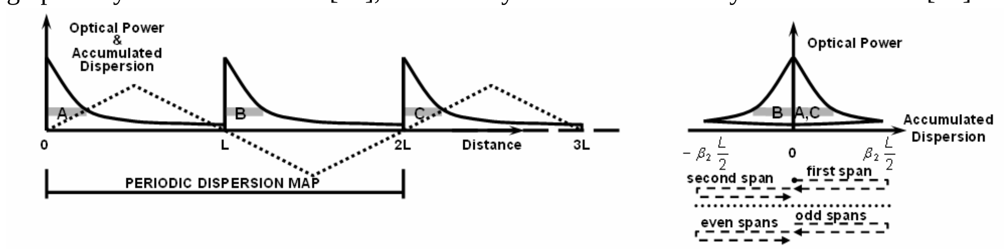

Fig. 8. Proposed dispersion map (left) and related PADD (right). Intra-span dispersion compensation, and inter-span nonlinearity compensation are obtained.

This scheme allows realizing substantial dispersion compensation on each span, and to compensate the nonlinear effects produced between two subsequent spans. To analyze the behavior of nonlinear effects into this dispersion map, the evolution of the EOP during propagation has been monitored. In Fig. 9 two links (18 spans 100km each) with a different dispersion management are reported. The first link, where the two fibers considered are F2 and F3, takes advantage of proposed dispersion map whereas second considered link is obtained using the same fibers, but doesn't produce symmetrical nonlinear regions because the same fiber configuration is repeated in each span.

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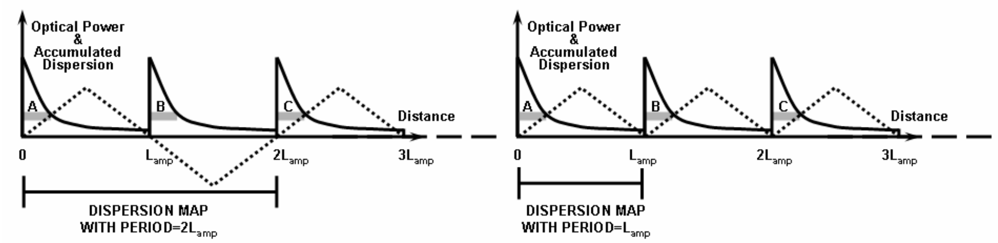

Fig. 9. Left: the identified dispersion map employ two fibers in each span and its period is twice the span length. This fiber arrangement allows producing a symmetrical PADD. Right: commonly used map yielding periodical dispersion compensation.

In the following figure the EOP and timing-jitter variation during propagation along previously described link is reported. It can be observed that (as graphically predicted) a periodical reduction of nonlinear effects can be obtained using proposed dispersion map. Conversely pulses propagating along the link with "asymmetrical nonlinear regions" experience a constant accumulation of nonlinear effects, producing a significant growth of the induced penalty.

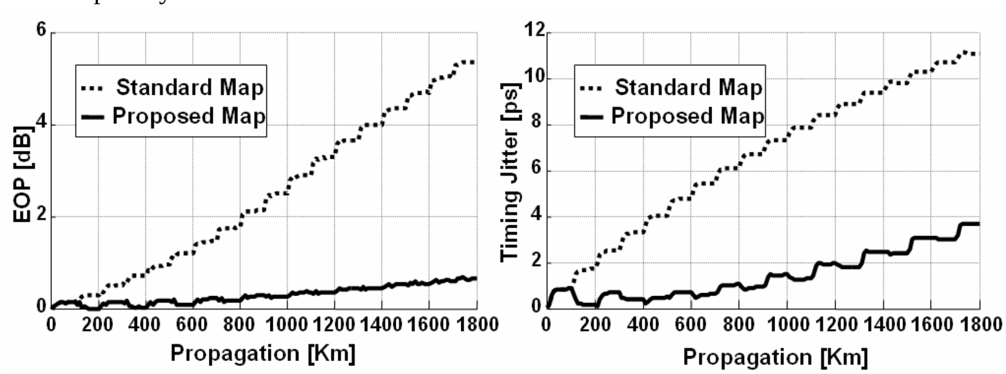

Fig. 10. Evolution, during propagation, of EOP and timing jitter in a standard map and in the map identified using the PADD

5. Conclusion

A new, graphical approach able to explain all known techniques for nonlinearity compensation has been disclosed. This method, derived from a generalization of the mid-span-spectral-inversion, is based on mid-nonlinearity-temporal-inversion and allows a fast identification of systems configuration producing nonlinearity compensation. Moreover it allows to overcome various implementation constraints (like unequal amplifier spacing or non periodic dispersion maps), thus proving useful also for the analysis of non-ideal systems.