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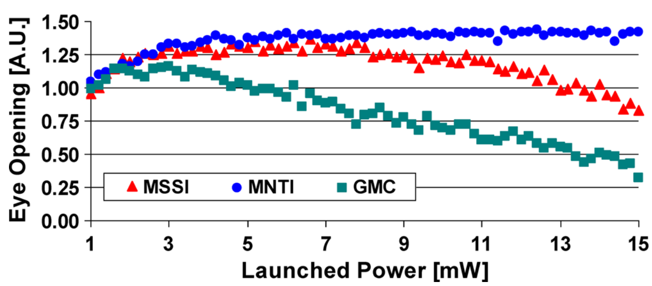

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Study of the Gordon–Mollenauer Effect and of the Optical-Phase-Conjugation Compensation Method in Phase-Modulated Optical Communication Systems

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Abstract: Optical phase-modulated systems are promising candidates for the development of ultrahigh-bit-rate transmission links, thanks to their high spectral efficiency and increased tolerance to fiber-optic nonlinearities. However, their implementation was considerably slowed down by theoretical studies, suggesting that the transmission performance can be severely hindered by nonlinear phase noise (the so-called Gordon–Mollenauer effect). The simulations presented here show that, in realistic systems (including nonlinearity, dispersion, and attenuation), Gordon–Mollenauer noise does not represent the main source of signal distortions. We demonstrate that all nonlinear impairments can be efficiently compensated by optical phase conjugation, independent of system characteristics. The combination of optical-phase-conjugation with phase-modulation formats could enable ultrahigh-transmission-capacity and easy embedded-link upgrading.

Index Terms: Phase modulation, Gordon–Mollenauer, optical phase conjugation, fiber-optic communications, Kerr effect, fiber nonlinear effects.

1. Introduction

At the present state of the art of fiber-optical communications, phase-modulated (PM) systems, in association with coherent detection and digital signal processing (DSP), are the foreseen solution for long-haul high-bit-rate transmission [1], [2].

Fiber-optic nonlinearities, and especially the Kerr effect, are the main source of impairment in very high-bit-rate transmission systems. Kerr nonlinearities induce an intensity-dependent (and hence time-varying) phase shift, which leads to the generation of new frequency components in the signal spectrum. The interplay between the new frequencies and the fiber chromatic dispersion produces a signal distortion that can strongly affect the signal quality. Since both optical dispersion and nonlinear interactions are deterministic effects, in principle, the signal distortion caused by these effects can be exactly compensated by an optical-phase-conjugation (OPC) operation that inverts the relative phase of the involved-field frequency components [3], [4]. The simplest approach is to perform OPC at mid-span [5], [6]. Such a technique, which is called mid-span spectral inversion (MSSI), has been indeed tested with some success, although subsequent works, both theoretical [7] and experimental [8], have demonstrated that, with lumped amplification, a more efficient compensation is achieved by using the approach called mid-nonlinearity temporal inversion (MNTI).

In addition to deterministic nonlinearities, PM systems suffer also the nonlinear phase noise, called Gordon–Mollenauer (GM) noise, due to the nonlinear interplay between the signal and the amplified spontaneous emission (ASE) emitted by the inline amplifiers [9]. Indeed, ASE adds linearly to the signal leading to an amplitude noise that is converted to phase noise through self-phase modulation. GM has peculiar characteristics, as the source of signal distortions is intrinsically statistical. Hence, in contrast with the distortions produced by the Kerr nonlinearity, GM full compensation cannot be achieved, even in an ideal case. Nevertheless, OPC-based partial compensation schemes have also been proposed for the case of GM noise [10]–[12]. The available theoretical studies of nonlinearity compensation in PM systems concern specific and rather unrealistic situations. In particular, we recall the theoretical analysis reported in [10], which shows that, under the hypothesis that the signal degradation is only due to GM noise (i.e., a perfectly flat power profile along the link and ideal soliton transmission), nonlinear distortions can be minimized by inserting an OPC device at two thirds of the link length. Hereafter, we will designate this approach as GM compensation (GMC). Up to now the results reported in the scientific literature do not help to clarify under which conditions the impairments introduced by the GM effect are really relevant [13]–[15]. Moreover, the few available experimental data on nonlinearity compensation in PM systems are not conclusive about the validity of the theoretical results regarding GMC by means of the OPC technique [11], [12], [16].

In this paper, we present the results of extended simulations concerning PM systems, in which we have studied not only the noise mechanisms but the compensation techniques based on OPC as well. Two different goals are here pursued. The first goal is to clarify the effect on the PM signal of different "distortion sources" such as ASE, the nonlinear effect, and the dispersion coefficient, and their interplay. It is generally assumed that GM represents a major impairment for PM formats. However, since the theoretical study by Gordon and Mollenauer only refers to idealized systems presenting no optical dispersion and no attenuation, it is very important to extend the analysis of the impairments to more general situations. Our results show that, in the case of realistic systems not employing special dispersion maps (all the accumulated dispersion is compensated at the receiver site), the GM effect is not the main source of signal distortion, and thus, it does not represent a real limitation to the development of PM optical communications. The second goal of our work is to analyze the effectiveness of OPC-based nonlinearity-compensation techniques in PM systems. We demonstrate that the nonlinear impairments affecting PM systems can be efficiently compensated by OPC, almost independently of system characteristics, the best performance being offered by the MNTI approach.

2. Noise and Signal Distortions in a PM Link

In order to devise a strategy for the compensation of all the distortions deriving from nonlinear phenomena in PM systems, it is essential to reach a clear understanding of their origin. For this reason, we have approached the problem by carrying out extensive simulations on the behavior of several optical-communication links (all 1800-km long, with 10-Gb/s transmission rate and 100-km amplifier spacing) with different characteristics in terms of optical launch power per span, modulation format, and fiber chromatic dispersion.

The simulations were performed by considering a 10-Gb/s non-return-to-zero differential phase-shift keying (NRZ-DPSK) signal. We note that NRZ-DPSK gives a constant amplitude signal, differently from the case of return-to-zero DPSK (RZ-DPSK) modulation, in which the signal is PM on a series of optical pulses with the same amplitude. Each span considered in the numerical simulations includes erbium-doped fiber amplifiers (EDFAs) periodically distributed along the system (every 100 km), with a noise figure $NF = 6$ dB, and an average output optical power of 4 mW ($\approx$6 dBm). At the end of every span, a Lorentzian optical filter with FWHM bandwidth of 200 GHz, centered on the signal frequency, has been inserted. This solution guarantees that the amplifiers

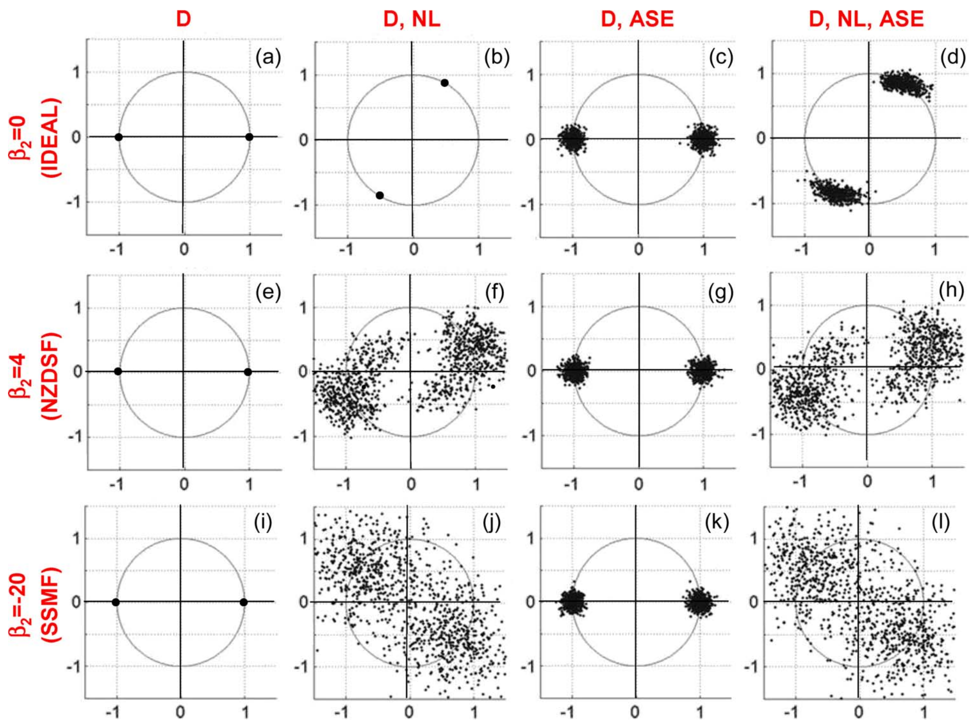

Fig. 1. Constellation diagrams obtained under different simulations conditions. The different rows refer to different values of the fiber chromatic dispersion. The first row (a)–(d) corresponds to the ideal situation in which the fiber dispersion is exactly zero, the second one (e)–(h) to a typical situation for a NZDSF link, and the third one (i)–(l) to the dispersion generally assumed for a SSMF system. Conversely, the different columns correspond to different combinations of effects taken into account in the pulse propagation equation. From left to right: dispersion only (a), (e), (i), dispersion and nonlinearity (b), (f), (j), dispersion and ASE (c), (g), (k), dispersion nonlinearity and ASE (d), (h), (l). The dots in the constellations (a), (b), (e), and (i) have been enlarged for the sake of clarity.

output power is mainly due to the signal and not to the amplification of wide-band ASE that is present in the simulation bandwidth introduced by the upstream amplifiers.

The transmitter was realized by introducing an ideal phase modulator, with 10-GHz bandwidth, driven by a 10-Gb/s 2^{10}-bit pseudorandom bit sequence, modulating a distributed feedback laser with an emission wavelength of 193.5 THz ($\sim$1550 nm) and an ideal linewidth of 0 nm. At the receiver, we have considered the presence of a 100-GHz-bandwidth optical Lorentzian filter, followed by an ideal pin photodiode and by a 7.5-GHz-bandwidth electric filter.

The adopted simulation tool, i.e., OPTSIM, is based on the standard nonlinear propagation equation [17]–[19], and it allows the selective introduction of different effects (ASE, nonlinearity, and dispersion) so that it is possible to evaluate their specific impact on the signal. In order to offer an intuitive view of the results, we have adopted a vectorial representation of the PM symbols in the complex plane: the so-called constellation diagram. Each symbol can be seen as a vector whose length gives the symbol amplitude normalized to the average amplitude of the symbol train and whose direction is determined by its phase. The constellation diagram shows the end points of the vectors. If an ideal signal is considered, and no distortion is present, all the points collapse into two single points (corresponding to the values associated to "0"s and "1"s, respectively). The presence of noise and distortions can hence be seen as a spread of end points.

The simulations results are displayed in Fig. 1, which shows 12 constellation diagrams obtained under different conditions, in terms of fiber-dispersion values and effects included in the simulations. We consider at first an ideal link with the dispersion coefficient set to zero ($\beta_2 = \beta_3 = 0$) and with an attenuation coefficient $\alpha = 0.2$ dB/km. If both ASE and nonlinearity are neglected, i.e., no source of distortion is present, the constellation diagram corresponding to the received signal is that reported in

Fig. 1(a). If only the Kerr effect is taken into account, as the signal intensity is constant and dispersion is absent, the same nonlinear phase shift is applied to each bit, thus causing the same rotation of each symbol, as shown in Fig. 1(b). On the opposite side, when only the effect of ASE is considered, and the Kerr effect is neglected, an uncertainty in the vector-end position of the DPSK signal can be observed as shown in Fig. 1(c). Finally, the result obtained in presence of both ASE and Kerr nonlinearity is shown in Fig. 1(d), clearly demonstrating that their interplay significantly increases signal distortion.

In order to make a quantitative comparison among different cases, and to focus the attention on the impact of GM, we compute the phase standard deviation Φ of the signal end vectors. As nonlinear phase noise has been shown to give to the constellation an "elongated" and not circular shape, the phase standard deviation appears to be the most direct way to assess this shape modification. While the value corresponding to the situation in Fig. 1(b) is null ($\Phi_{NL} = 0$), the values obtained for Fig. 1(c) (Φ_{ASE}) and Fig. 1(d) (Φ_{ASE+NL}) are 4.84° and 9.93°, respectively. In such an ideal situation where dispersion has been neglected, the GM noise due to the interplay between ASE and nonlinearity is hence a major source of impairment.

We performed the simulations including dispersion with two different types of fiber; we considered a nonzero dispersion fiber (NZDSF, ITU-T G.655) with $\beta_2 = +4$ ps^2/km and a standard single-mode fiber (SSMF, ITU-T G.652) with $\beta_2 = -20$ ps^2/km. In order to highlight the effect of the fiber chromatic dispersion, we considered in both cases $\beta_3 = 0$ ps^2 nm^{-1} km^{-1} and $\gamma = 1.26$ W^{-1} km^{-1}. The obtained constellation diagrams for NZDSF are shown in Fig. 1(e)–(h), while those regarding SSMF are reported in Fig. 1(i)–(l). It can be observed that in the NZDSF link the performance is considerably degraded in presence of nonlinearity. Conversely, the introduction of ASE implying the involvement of the GM effect does not lead to significant additional impairments. A similar situation is found for the SSMF system [Fig. 1(i)–(l)], where the interplay between dispersion and nonlinearity has even more dramatic effects: as the amplitude fluctuations become stronger, they produce severe phase-variation impairments, making the influence of GM noise completely negligible [no evident worsening can be seen comparing Fig. 1(j) and (l)]. It is worth underlining that, differently from other papers on GM impact, we have considered no "noise-loading" stage, neither at the transmitter nor at the receiver, as they are not used in real fiber transmission systems, and their presence can significantly modify the signal propagation, thus making it easy to derive incorrect conclusions [16].

3. OPC Compensation in a PM Link

The second step of our simulation study was the introduction of the OPC device into the link in order to compensate for signal distortions. To this aim, we have modeled an ideal optical phase conjugator (i.e., not introducing any signal distortion or noise) that simply reverses the sign of the imaginary part of incoming signal, and we have carried out signal-transmission simulations including fiber attenuation, dispersion (β_2 only), and noise effect. Three different OPC-based techniques have been implemented: MSSI, MNTI, and GMC.

The MSSI technique, as mentioned above, consists of the insertion of the OPC device exactly at the midpoint of the link [3]–[6]. The compensation is completely effective under some strict requirements: the fiber characteristics should be identical in the whole transmission system, and the transmission link must be lossless, or at least with a "perfectly symmetrical" distribution of the optical power along the fiber line with respect to the midpoint. While the first two hypotheses can be somehow accomplished by using a properly designed fiber transmission system, the realization of a lossless system, or of symmetrical power profiles, is extremely impractical.

MNTI represents a different approach that is applicable to real links without strong system constraints. MNTI focuses on the diagram of optical power versus accumulated dispersion (PADD) and imposes a symmetrical distribution of the nonlinear regions with respect to the zero value of the accumulated group velocity dispersion (GVD). The symmetrical distribution of the nonlinear regions on the PADD can be easily achieved by inserting the OPC device in a precise position, which is generally close to the middle of the link and determined by the distribution of the optical power along the fiber line and, hence, by the attenuation coefficient of the optical fibers. Since for the two fibers

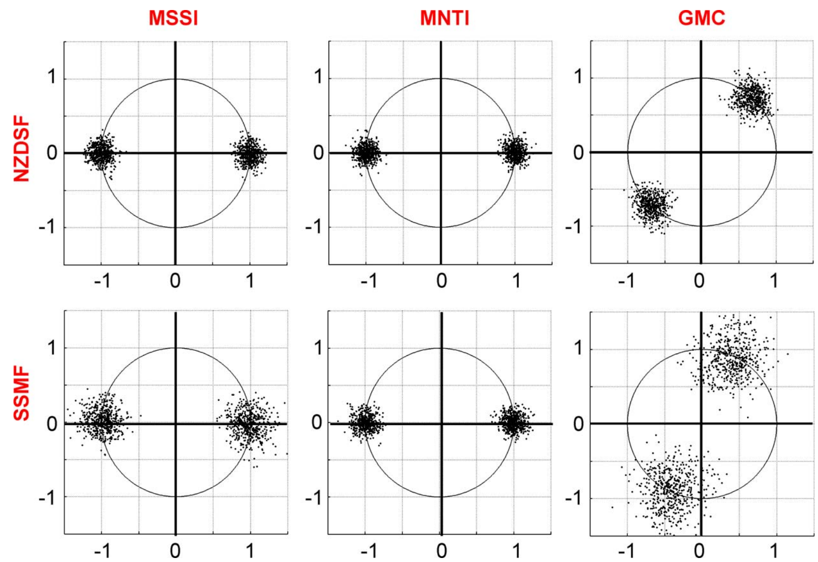

Fig. 2. Constellation diagrams obtained by the numerical simulation of the three different nonlinearity compensation techniques with different types of fiber. The constellation diagrams obtained without taking advantage of the OPC insertion are those reported in Fig. 1(h) (for NZDSF) and Fig. 1(l) (for SSMF).

we considered the same attenuation coefficients, the chosen OPC position is the same for both cases. It is worth noticing that, in real transmission links, MNTI can be implemented without accessing the system in the middle of an installed span but by putting the OPC device at the closest amplification site. For this reason, as discussed in [8], [16], and [20], the MNTI method is particularly suitable for the upgrade of existing systems (without inline dispersion compensation) up to 20-Gb/s or 40-Gb/s transmission rates, independently of the exact bit rate and modulation format. The effectiveness of this technique has never been tested with PM systems.

The GMC technique, which was developed for PM soliton transmission systems and discussed in [10], predicts the optimal OPC position at two thirds of the total link length. Both MNTI and GMC configurations require full compensation of the uncompensated chromatic dispersion at the receiver, which is ensured by proper fiber modules, considered as ideal, purely dispersive elements. Attenuation and nonlinear effects have not been considered in the dispersion-compensating modules. It is noteworthy that in GMC a considerable amount of residual dispersion needs to be compensated at the receiver, which corresponds to the propagation along one third of the link. On the contrary, in MNTI, the residual dispersion at the receiver is very small, since the OPC position is close to the link's physical midpoint.

In our simulations, the OPC device is inserted exactly at 900 km to implement the MSSI technique, at about 860 km for MNTI implementation, and at 1200 km for testing the GMC technique.

Fig. 2 shows the constellation diagrams obtained by applying the three approaches to both the NZDSF and SSMF links. In both cases, the configurations yielding to the best result is MNTI ($\Phi_{\mathrm{NZDSF}} = 5.28^\circ$, $\Phi_{\mathrm{SSMP}} = 5.47^\circ$), while MSSI presents larger standard deviations ($\Phi_{\mathrm{NZDSF}} = 5.53^\circ$, $\Phi_{\mathrm{SSMF}} = 9.68^\circ$).

It is interesting to note that the performance difference between MNTI and MSSI becomes larger when the dispersive effects are more relevant [7], [20]. This is due to the fact that, if we consider a "low-dispersion" case, the signal temporal shape does not change significantly between 862 km (OPC-site for MNTI) and 900 km (OPC-site for MSSI), as the distance between these two points is much shorter than the signal dispersion length [21], and no nonlinear effect is present because the optical power in the last part of the fiber span is much lower than in the first section. Conversely, considering "high dispersion" (or very short pulses), the dispersive effects accumulated between

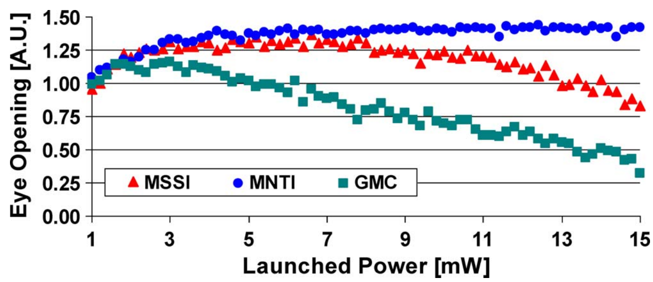

Fig. 3. Eye opening versus optical power launched into each span of the system, considering the NZDSF link. It can be seen that the eye opening obtained using the MNTI configuration is always larger than that given by the use of the other two approaches. All the curves reach the zero level for a sufficiently large launched power (not shown in the figure).

the MNTI and MSSI positions can produce significant changes in the signal temporal profile, thus significantly affecting the nonlinearity compensation efficiency.

It is also evident that the GMC approach brings only a modest reduction of nonlinear impairments, leading to larger Φ values and not compensating for the fixed phase shift due to self-phase modulation, which results in a constellation rotation as can be seen in the third column of Fig. 2. The poor performance of the GMC approach can be explained by considering that the interplay between nonlinearity and dispersion makes the power evolution along the link similar to that of standard OOK systems, which is strongly different from the theoretical conditions depicted in [10].

It should be underlined that in all the simulations, the third-order dispersion effect has been neglected. This omission makes it simpler to realize a comparison between the different OPC-based techniques and the results obtained without OPC; anyway, it must be recalled that OPC does not allow, in a general case, compensating for fiber third-order dispersion. A discussion about the effect of third-order dispersion on OPC-based systems, and nonlinearity compensation, can be found in [22]. The results reported in [22] highlight that even in presence of multichannel transmission, and taking into consideration the presence of third-order dispersion, the MNTI approach allows a significant nonlinearity compensation, which is not achievable with the MSSI approach.

To better investigate the performance of the three OPC configurations, also for different values of the optical power, we have analyzed the received eye-opening parameter, (i.e., the difference between the minimum power associated to a “1” and the maximum received power corresponding to a “0”) for a fixed value of the optical power input to the photodiode, as a function of the inline amplifiers output optical power. This parameter has been judged to reliably describe the system performance, given the large number of transmitted symbols. At the receiver, the optical signal is filtered (using a Lorentzian filter with a FWHM bandwidth of 100 GHz), demodulated by a Mach–Zehnder delay interferometer, optically amplified to reach a fixed power level, and then sent to an ideal pin photodiode, followed by an electrical filter with 7.5-GHz bandwidth. The analysis has been carried on for both the NZDSF and the SSMF links. The obtained results are reported in Figs. 3 and 4, respectively.

By looking at the curves reported in Fig. 3 we can observe that, for low optical power (e.g., 1 mW), the performance of the three configurations is very similar. In such a case, if the dispersive effects are properly compensated, the nonlinear impairment accumulated during signal propagation is negligible, and as a consequence, the use of different nonlinearity-compensation strategies does not affect the system performance to a great extent. On the opposite side, when the output optical power of the amplifiers is increased, the differences between the achieved performances become more evident. In particular, in accordance with the previous results, the best performance is achieved using MNTI, while the worst one uses the GMC approach.

Similar conclusions can be drawn on the SSMF link. Also, in this case, the best performance is obtained using MNTI configuration, followed, in order, by MSSI and GMC. It is interesting to notice

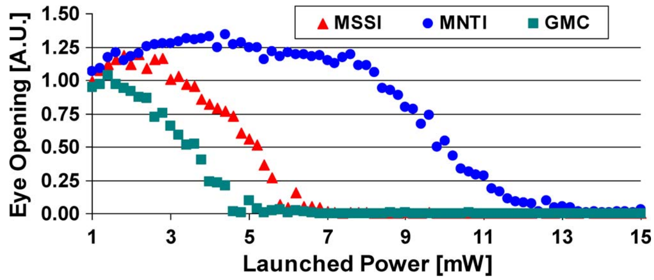

Fig. 4. Eye opening versus optical power launched into each span of the system, considering the SSMF link. It can be seen that the eye opening obtained using the MNTI configuration is always larger than that given by the use of the other two approaches. As the SSMF link is more sensitive to the fiber nonlinear effects, with respect to the NZ-DSF one, all the curves decrease more rapidly than those reported in the previous figure.

that, as observed in Fig. 2, the performance difference between MNTI and MSSI significantly increases when a fiber with higher dispersion (SSMF versus NZDSF) is considered.

The same result has also been observed comparing, for a given fiber, the different curves obtained considering RZ and NRZ pulses (data not reported in this paper). When RZ pulses are used, a larger performance difference between MNTI and MSSI is present, as RZ pulses are more sensitive to dispersion than NRZ ones.

4. Conclusion

We have analyzed the impact of different impairment sources on PM systems with different characteristics in terms of fiber chromatic dispersion, modulation format, and optical launch power. In particular, we have found that the GM effect is dominant only in transmission systems where the optical pulses undergo a negligible modification of their amplitude, thanks to the use of ideal "dispersionless" fibers, to the realization of perfect soliton transmission, or of specific dispersion maps. As the pulse distortion produced by the fiber dispersion becomes significant, as it happens in real systems, other nonlinear impairments dominate, and the penalty produced by the GM effect can generally be neglected.

Moreover, we have also analyzed the efficacy of three different OPC-based techniques on the compensation of the nonlinearity-induced distortions. By using the constellation-diagram representation of the simulation results, we have obtained a simple and straightforward evaluation of the OPC-compensation effectiveness, and we have predicted the optimal link configuration. We have found that the combination of OPC with PM formats is a promising solution for enabling ultrahigh transmission capacity and easy embedded-link upgrading. This result could significantly impact future transmission-link design and the general assessment of penalties induced by fiber-optic nonlinearities. Experimental demonstration of the obtained results is currently ongoing; further analysis on the extension of this technique to WDM systems with a higher channel bit rate has been planned.

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