Optimal packing for cascaded regenerative transmission based on phase sensitive amplifiers

Mariia Sorokina,* Stylianos Sygletos, Andrew D. Ellis, and Sergei Turitsyn

Aston Institute of Photonic Technologies, Aston University, B4 7ET Birmingham UK

**sorokinm@aston.ac.uk*

Abstract: We investigate the transmission performance of advanced modulation formats in nonlinear regenerative channels based on cascaded phase sensitive amplifiers. We identify the impact of amplitude and phase noise dynamics along the transmission line and show that after a cascade of regenerators, densely packed single ring PSK constellations outperform multi-ring constellations. The results of this study will greatly simplify the design of future nonlinear regenerative channels for ultra-high capacity transmission.

OCIS codes: (060.2330) Fiber optics communications; (060.5060) Phase modulation; (190.4970) Parametric oscillators and amplifiers.

References and links

1. R. Tkach, "Scaling optical communications for the next decade and beyond," Bell Labs Tech. J. **14**(4), 3–9 (2010).
2. D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," Nat. Photonics **7**(5), 354–362 (2013).
3. P. J. Winzer and R. J. Essiambre, "Advanced modulation formats for high-capacity optical transport networks," J. Lightwave Technol. **24**(12) 4711–4728 (2006).
4. R. J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," J. Lightwave Technol. **28**(4), 662–701 (2010).
5. T. Roethlingshoefer, G. Onishchukov, B. Schmauss, and G. Leuchs, "Multilevel amplitude and phase regeneration in a nonlinear amplifying loop mirror with a phase-Sensitive Amplifier," in *Proceedings of European Conference on Optical Communication (ECOC 2012)*, Amsterdam, paper Tu.1.A.3 (2012).
6. S. Sygletos, P. Frascella, S. K. Ibrahim, L. Gruner-Nielsen, R. Phelan, J. O'Gorman, and A. D. Ellis, "A practical phase sensitive amplification scheme for two channel phase regeneration," Opt. Express **19**(26), 938-945 (2011).
7. K. S. Turitsyn and S. K. Turitsyn, "Nonlinear communication channels with capacity above the linear Shannon limit," Opt. Lett. **37**(17), 3600–3602 (2012).
8. X. Chen and W. Shieh, "Closed-form expressions for nonlinear transmission performance of densely spaced coherent optical OFDM systems," Opt. Express **18**(18), 19039–19054 (2012).
9. D. Rafique and A. D. Ellis, "Impact of signal-ASE four wave mixing on the effectiveness of digital back-propagation in 112 Gbit/s PM-QPSK systems," Opt. Express **19**(4), 3449–3454 (2011).
10. H. Louchet, A. Hodzic, and K. Petermann, "Analytical model for the performance evaluation of DWDM transmission systems," IEEE Photonics Technol. Lett. **15**(9), 1219–1221 (2003).
11. A. Splett, C. Kurtzke, and K. Petermann, "Ultimate transmission capacity of amplied optical ber communication systems taking into account ber nonlinearities," in *Proceedings. European Conference on Optical Communication (ECOC 1993)*, paper MoC2.4. (1993).
12. P. Poggiolini, A. Carena, V. Curri, G. Bosco, and F. Forghieri, "Analytical modeling of non-linear propagation in uncompensated optical transmission links," IEEE Photonics Technol. Lett. **23**(11), 742–744 (2011).
13. P. P. Mitra and J. B. Stark, "Nonlinear limits to the information capacity of optical fibre communications," Nature **411**(6841), 1027–1030 (2001).

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

14. E. Torrengo, R. Cigliutti, G. Bosco, A. Carena, V. Curri, P. Poggiolini, A. Nespola, D. Zeolla, and F. Forghieri, "Experimental validation of an analytical model for nonlinear propagation in uncompensated optical links," in *Proceedings of European Conference on Optical Communication (ECOC 2011)*, Amsterdam, paper We.7.B.2 (2011).
15. A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," IEEE J. Lightwave Technol. **28**(4), 423–433 (2010).
16. A. Mecozzi and R.J. Essiambre, "Nonlinear Shannon limit in pseudo-linear coherent systems," IEEE J. Lightwave Technol. **30**(12), 2011–2024 (2012).
17. L. Beygi, E. Agrell, and M. Karlsson, "On the optimization of 16-point ring constellations in the presence of non-linear phase noise," in *Proceedings of Optical Communication Conference*, 2011 OSA Technical Digest Series (Optical Society of America), paper OThO4 (2011).
18. E. Agrell and M. Karlsson, "Satellite constellations: towards the nonlinear channel capacity," in *Proceedings of IEEE Photonics Conference*, 2012, paper TuM1.
19. H. J. Thiele, A. D. Ellis, and I. D. Phillips, "Recirculating loop demonstration of 40 Gbit/s all-optical 3R data regeneration using a semiconductor nonlinear interferometer," Electron. Lett. **35**(3), 230–231 (1990).
20. I. D. Phillips, A. Gloag, P. N. Kean, N. J. Doran, I. Bennion, and A. D. Ellis, "Simultaneous de-multiplexing, data regeneration and clock recovery using a single semiconductor optical amplifier based nonlinear optical loop mirror," Opt. Lett. **22**(17), 1326–1328 (1997).
21. I. Kang, C. Dorrer, L. Zhang, M. Rasras, L. Buhl, A. Bhardwaj, S. Cabot, M. Dinu, X. Liu, M. Cappuzzo, L. Gomez, A. Wong-Foy, Y. F. Chen, S. Patel, D. T. Neilson, J. Jacques, and C. R. Giles, "Regenerative all optical wavelength conversion of 40 Gbit/s DPSK signals using a SOA MZI," in *Proceedings of European Conference on Optical Communication (ECOC 2005)*, Amsterdam, paper Thu 4.3.3 (2005).
22. D. Wolfson, P. B. Hansen, A. Kloch, T. Fjelde, C. Janz, A. Coquelin, I. Guillemont, F. Gaborit, and M. Renaud, "All-optical 2R regeneration at 40 Gbit/s in an SOA-based Mach-Zehnder interferometer," in *Proceedings of Optical Communication Conference*, Beijing, pp. 456-457 (1999).
23. M. Matsumoto, "Fiber-based all-optical signal regeneration," IEEE J. Sel. Top. Quantum Electron. **18**(2), 738–752 (2012).
24. O. Leclerc, U. E. Desurvire, and O. Audouin, "Synchronous WDM soliton regeneration: toward 80–160 Gbit/s transoceanic systems," Opt. Fiber Technol. **3**(2), 97–116 (1997).
25. S. Boscolo, K. J. Blow, and S. K. Turitsyn, "All-optical passive 2R regeneration for Nx40 Gbit/s WDM transmission using NOLM and novel filtering technique," Opt. Commun. **217**, 227–232 (2003).
26. M. Nakazawa, E. Yamada, H. Kubota, and K. Suzuki, "10 Gbit/s soliton data transmission over one million kilometres," Electron. Lett. **27**(14), 1270–1272 (1991).
27. K. Croussore, C. Kim, and G. Li, "All-optical regeneration of differential phase shift keying signals based on phase-sensitive amplification," Opt. Lett. **29**(20), 2357–2359 (2004).
28. R. Slavik, F. Parmigiani, J. Kakande, C. Lundstrom, M. Sjodin, P. Andrekson, R. Weerasuriya, S. Sygletos, A. D. Ellis, L. Gruner-Nielsen, D. Jakobsen, S. Herstrom, R. Phelan, J. O'Gorman, A. Bogris, D. Syvridis, S. Dasgupta, P. Petropoulos, and D. Richardson, "All-optical phase and amplitude regenerator for next generation telecommunications systems," Nat. Photonics **4**(10), 690-695 (2010).
29. J. Kakande, R. Slavik, F. Parmigiani, A. Bogris, D. Syvridis, L. Gruner-Nielsen, R. Phelan, P. Petropoulos, and D. J. Richardson, "Multilevel quantization of optical phase in a novel coherent parametric mixer architecture," Nat. Photonics **4**(12), 748-752 (2011).
30. T. Umeki, M. Asobe, H. Takara, Y. Miyamoto, and H. Takenouchi, "Multi-span transmission using phase and amplitude regeneration in PPLN-based PSA," Opt. Express **21**(15), 18170–18177 (2013).
31. C. E. Shannon, "A mathematical theory of communication," Bell Syst. Tech. J. **27**, 379–423 (1948).
32. M. A. Sorokina and S. K. Turitsyn, "Shannon capacity of nonlinear regenerative channels," arXiv:1305.1537.
33. G. P. Agrawal, *Nonlinear Fiber Optics* (Springer, 2000).
34. E. Desurvire, D. Bayart, B. Desthieux, and S. Bigo, *Erbium-Doped Fiber Amplifiers: Device and System Developments* (John Wiley, 2002).
35. M. A. Sorokina, S. Sygletos, and S. K. Turitsyn, "Optimization of cascaded regenerative links based on phase sensitive amplifiers," Opt. Lett. **38**(20), 4378–4381 (2013).
36. A. Bogris and D. Syvridis, "All-optical signal processing for 16-QAM using four-level optical phase quantizers based on phase sensitive amplifiers," in *Proceedings of European Conference in Optical Communications (ECOC 2013)*, London, paper We.3A.6 (2013).
37. M. C. Jeruchim, "Techniques of estimating the bit error rate in the simulation of digital communication systems," IEEE J. Sel. Top. Quantum Electron. **2**(1), 153–170 (1984).

1. Introduction

The exponentially increasing data traffic due to extensive use of broadband services imposes a continuing pressure for technological innovation in the physical layer of the optical network to meet the future high capacity demands. With the optical transmission bandwidth being limited to ~ 5 THz by the commercially available erbium doped fiber amplifier technology, a dramatic increase in the spectral efficiency of the transmission link will be required [1]. At the same time, the need to maintain a reducing cost per bit of transmitted data suggests that any serious attempt to upgrade system capacity should start from legacy network infrastructures before going to major deployments of new fiber cables, e.g. by adopting space division multiplexing technologies [2]. The use of modulation formats with multi-level signaling represents a technologically mature and cost efficient way to achieve this goal [3]. However, increasing the constellation complexity makes the signal more vulnerable to amplified spontaneous emission (ASE) noise and to a variety of linear and nonlinear fiber link impairments [4]. Therefore, to support transmission over long distances frequent use of in-line regeneration will be unavoidable. To minimize cost, in-line regeneration would ideally be compatible with complex constellations [5] and operate over multiple wavelengths simultaneously [6]. Such features are most likely to be the result of all-optical approaches, making the use of advanced forward error correction (FEC) at regeneration site difficult. Considering a fiber channel as the link between two nodes implementing FEC, all-optical regenerators would result in future high capacity fiber channels being highly nonlinear [7] even in the absence of nonlinear transmission impairments such as those considered in [1–4] and [8–16].

Thus, a new channel type arises, which we call regenerative channel, where optimization of signal modulation and coding is crucial for high capacity transmission. Contrary to the well known linear cases or conventional nonlinear channels, where continuous bi-Gaussian constellations or ring constellations have respectively proved to be the optimum solution [4], for regenerative channels the problem still remains unsolved. Even for the conventional nonlinear-channel, where nonlinearity plays only a detrimental role in signal transmission, significant benefits in capacity can be acquired by optimizing the modulation format [7], [17–18]. In regenerative channels, where nonlinearity has a higher and constructive impact, a stronger connection between the input modulation and the system parameters should be expected.

Up-to-date, a number of regeneration techniques have been proposed making use of different nonlinear device technologies, e.g. semiconductor optical amplifiers (SOAs) [19–22] or fibers [23–29] in various subsystem configurations, e.g. Mach-Zehnder [21-22] or non-linear loop mirrors (NOLMs) [24–26]. It has been shown [19], [24–26], [30] that most of them can support large regenerator cascades and bring significant improvements in the overall system capacity and transmission distance. However, they were primarily designed to address binary channels offering optimization only in the amplitude and pulse shape of the optical signal. Recent developments in all-optical signal processing have created a new type of nonlinear element, i.e. the phase sensitive amplifier (PSA) [27–29], which can provide multi-level nonlinear response in the phase of the input optical field [29],[5]. Due to this property PSA technology is compatible with a broader variety of signal constellations than binary ASK regenerators and can support the development of digital fiber links for long haul transmission at much higher spectral efficiencies. Recent experiments [30] have already demonstrated a cascadability of more than 100 PSA elements enabling transmission of BPSK signals over distance larger than 5000 km. For higher spectral efficiencies a careful selection of the modulation format is required, due to the strong interplay between the noise and the non-linear transfer function of the PSA, to improve the overall transmission performance beyond the limits of linear [31] and nonilnear optical channels [13], [7], [32].

In this paper we have addressed the aforementioned problem by investigating signal transmission along digital channels formed by cascaded PSAs. Through extensive numerical simulations we compared the performance of a variety of 8- and 16- symbol constellation diagrams and discussed how their performance is affected by the number of cascaded nonlinear ele-

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

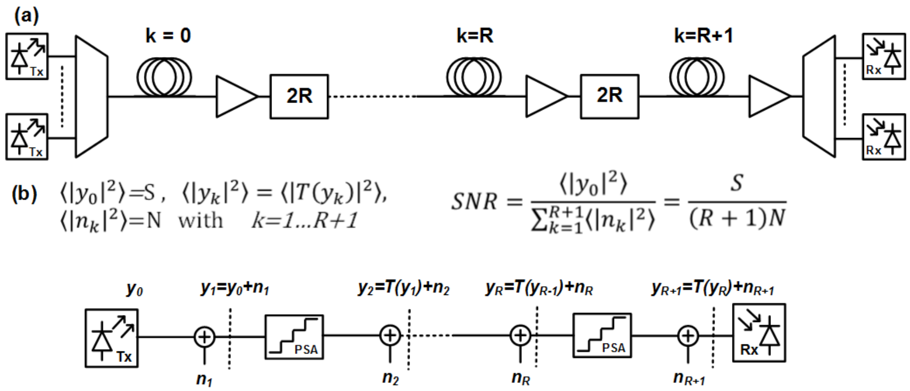

Fig. 1. (a) Schematic diagram of a future high capacity digital link formed by cascading R PSA based 2R- regenerators, R+1 links, each comprising a number of optically amplified spans adding noise with variance N, (b) Representation of simplified simulation model.

ments. We showed that as the number of phase regenerators increases along the transmission link densely packed phase shift keying formats outperform formats with multilevel quadrature amplitude modulation.

2. Simulation model

We have considered a transmission system of identical cascaded 2R regenerators based on PSA technology placed equidistantly along the fiber link, see Fig. 1(a). Since the goal of this study is to capture the main performance features of the transmission system and to focus on the impact of the signal regenerative mechanisms in the selection of the optimum format, a simplified representation of the full system model has been adopted. According to this, PSAs have been modeled by static elements of specific amplitude and phase response [29] and the impairments by additive white Gaussian noise (AWGN). AWGN can be considered as a representation not only of the amplified spontaneous emission noise [33–34] (linear channel between regenerators), but also of the inter-channel distortions due to Kerr nonlinearity in the fiber (nonlinear channel between regenerators) [8], as well as, of the signal-nonlinear noise interactions that might also arise [9]. The validity of the approach has been verified both theoretically [8–13] and experimentally [14], and it has been widely used for estimating capacity limits in nonlinear fiber channels [13], [15], [16].

Figure 1(b) illustrates the details of the proposed simplified simulation model. The propagation of the complex signal y_k at the k^{th} $(k = 1...R+1)$ regenerative section is described by the stochastic equation $y_k = T(y_{k-1}) + n_k$, where T is the regenerative transfer function of the PSA and n_k is the zero-mean AWGN noise of the k-th section with variance N, and S is the average signal power at the input of the transmission link. We assume that within each section the fiber loss of each span is compensated by subsequent amplifier and that deterministic impairments are ideally removed. We also note that our proposed model is generic and it can be used for various set of parameters and amplification schemes. Whilst this paper is focused on the effectiveness of the noise suppression mechanisms rather than the origins of the Gaussian noise itself, effective channel signal to noise ratios may be readily calculated from physical link parameters using the conventional formalism. Thus for simplicity, the point-to-point transmission system may be characterized by a single parameter, i.e. the signal-to-noise ratio (SNR),

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

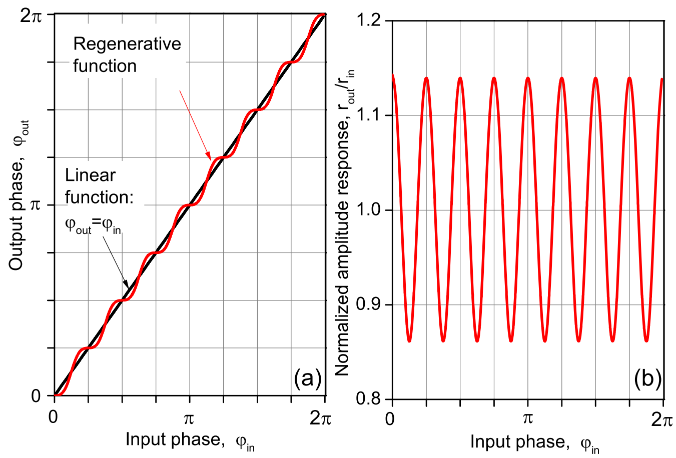

Fig. 2. (a) Normalized phase response and (b) normalized amplitude response of an 8-level phase sensitive amplifier as a function of the phase of the input signal.

defined as the ratio of the average signal power at the input of the transmission system to the total power of the linearly added noise along the line:

$$SNR = \frac{< |y_0|^2 >}{\sum_{k=1}^{R+1} < |n_k|^2 >} \tag{1}$$

This is equivalent to the signal to noise ratio of the corresponding linear system, i.e. at the absence of regenerative elements, it is directly related to the total system length, and it can provide a common reference for a fair comparison of systems with different regenerative properties. Each PSA is modeled as an M-level phase quantizer, which can be practically realized by a dual pump non-degenerate four wave mixing scheme of the input signal $r_{in}e^{i\varphi_{in}}$ with its $(M-1)$ – order harmonic (idler) [29]. Assuming operation in the linear regime of the amplifier, i.e. the signal power is much lower than the power of the local pumps, the PSA transfer function is given by:

$$r_{out}e^{i\varphi_{out}} = T\left(r_{in}e^{i\varphi_{in}}\right) = r_{in}e^{i\varphi_{in}}\left(1 + me^{-iM\varphi_{in}}\right) \tag{2}$$

To ensure that the average signal power is not changed by the regenerative transformation, the signal $T(y_k)$ at the output of each PSA is normalized so that $< |y_k|^2 >=< |T(y_k)|^2 >$. Note that the regenerative function depends only on the phase of the input signal. The parameter m represents the amplitude ratio between the signal and its idler and has a critical role in defining the phase noise suppression properties of the PSA. Our recent analytical study [35] has identified $m = 1/(M-1)$ as the optimum value, which provides a flat phase response at the alphabet points of the signal, enabling maximum phase noise suppression and regenerative performance along the link. The amplitude and phase response of an 8-level PSA with an optimized m-parameter are depicted in Figs. 2(a) and 2(b). Its phase response has a periodic staircase shape with plateau regions around the signal alphabet points. This periodicity suggests that only constellation diagrams with phase symmetry can be handled by the specific PSA scheme, although it can become the building block of more complex configurations that will allow dealing with rectangular M-QAM signals [36].

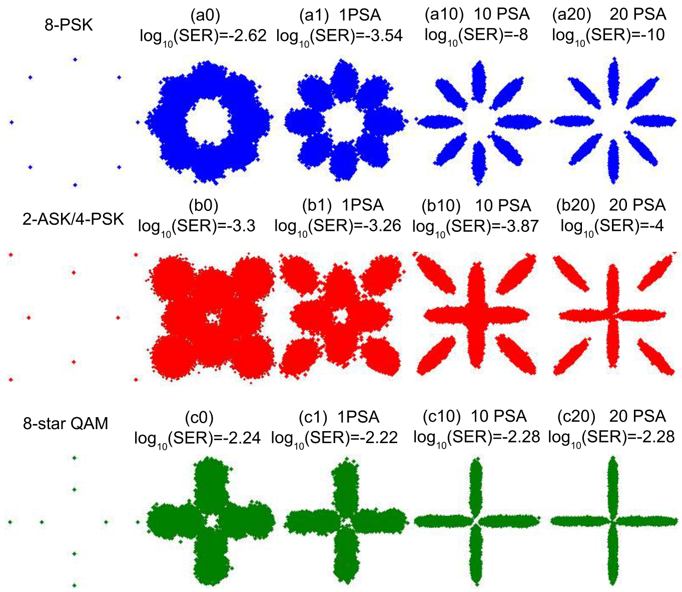

Fig. 3. Phase symmetric constellations for 8-symbols before (leftmost) and after transmission in linear channels and nonlinear regenerative channels with cascaded 1, 10, 20 phase regenerators for the fixed value of SNR =15 dB.

In the considered regenerative system we have investigated numerically the transmission of different advanced modulation formats and have compared their performance by calculating the symbol error rate (SER) at the receiving end. The SER has been chosen as the most suitable figure of merit for performance characterization as it reflects directly the impact of regeneration on the transmitted symbols and enables comparison of different constellation diagrams, including those for which coding (including Grey coding) has not been yet developed. The SER has been calculated using the Monte Carlo method [37] on transmitted 2^{23}-length sequences of randomly generated symbols. The long sequence length ensured a confidence interval better than 99 $^{\circ}/_{\circ}$ for the SER estimator even at values of 10^{-6}.

3. Results and discussion

We start our analysis by investigating the transmission performance of three different 8-symbol constellations with phase symmetry, as a function of the number of cascaded PSA regenerators in the link. The single ring 8-PSK is compared against the 2-ASK/4-PSK and 8-star QAM formats [4], which combine phase shift keying and amplitude shift keying modulation. To make the comparison fair the average symbol energy was kept the same for all these cases. Figure 3 shows the corresponding constellation diagrams and symbol error rates (SER) calculated at fixed SNR=15dB for the linear system (index 0), and when having a single, 10, and 20 regenerators in the link, indicated by respective indexes. The impact of PSAs in suppressing phase noise is apparent in each constellation and it becomes more effective when the number of in-line regenerative elements is increased. However, this does not necessarily bring improvement in the symbol error rate performance. From three examined cases, the PSK format experiences the largest improvement as its $\log_{10}(SER)$ drops from - 2.62 for the linear system to -10 after inserting 20 equally spaced PSA regenerative elements into the same system. For the 2-ASK/4-

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013
(C) 2013 OSA 16 December 2013 | Vol. 21, No. 25 | DOI:10.1364/OE.21.031201 | OPTICS EXPRESS 31206

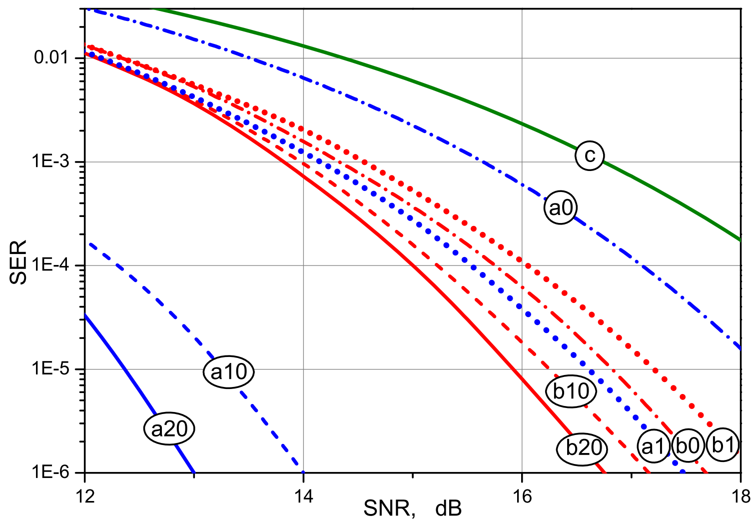

Fig. 4. SERs as a function of SNR for the examined 8-symbol constellation types; 1 amplitude level: 8-PSK (index a, blue lines), 2 amplitude levels: 2-ASK/4-PSK (index b, red lines), and 4 amplitude levels: 8-star QAM (index c, green line) for linear channel (sub-index 0) and nonlinear regenerative channels with cascaded 1, 10, 20 phase regenerators (sub-indexes 1, 10, and 20 respectively). Formats are also identified by line color, whilst the number of regenerators in the link is identified by the dashing of the line (dash length increases with number of regenerators).

PSK the SER improves significantly less in comparison to the non-regenerated case, whilst for the 8-star QAM the improvement is negligible for regenerators with either M=4 or M=8 (M=4 is shown above). This is because the latter two formats are more susceptible to amplitude distortions, which remain unsuppressed along the transmission line and, moreover, their performance is further degraded by the phase-to-amplitude conversion mechanism in the PSA, see Fig. 2(b).

The SER performance of the 8-star QAM cannot be improved due to the dominance of unsuppressed amplitude noise see curves c10 and c20 in Fig. 3. Therefore, their use is not suitable for PSA based regenerative links as it brings negligible impact in performance improvement. Furthermore, despite the $\pi/4$ phase shift the points of the 2-ASK/4-ASK constellation have experienced, the robustness of the format against amplitude distortion has not been increased due to the erroneous transitions between the inner ring points (see constellations with index b in Fig. 3), that are still high and affect the overall SER performance.

The SER as a function of the SNR for the aforementioned 8-symbol constellations and for different number of regenerative elements is shown in Fig. 4. As expected, in the absence of in-line regeneration the best performing format is the 2-ASK/4-ASK, followed by the 8-PSK and then the 8-star QAM. Placing a phase regenerator in the middle of the link changes this order as the 8-PSK is improved significantly in contrast to the other two cases. For the latter formats a slight SER degradation is noticed, due to phase-to-amplitude noise conversion. The influence of this mechanism can be moderated by cascading more PSA elements in the link to bring down the average phase noise power so that a minimum amount of additional amplitude noise is created.

We have analyzed further the amplitude and phase distortion dynamics of the aforementioned constellations at the receiver as a function of the number of cascaded regenerators in the

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

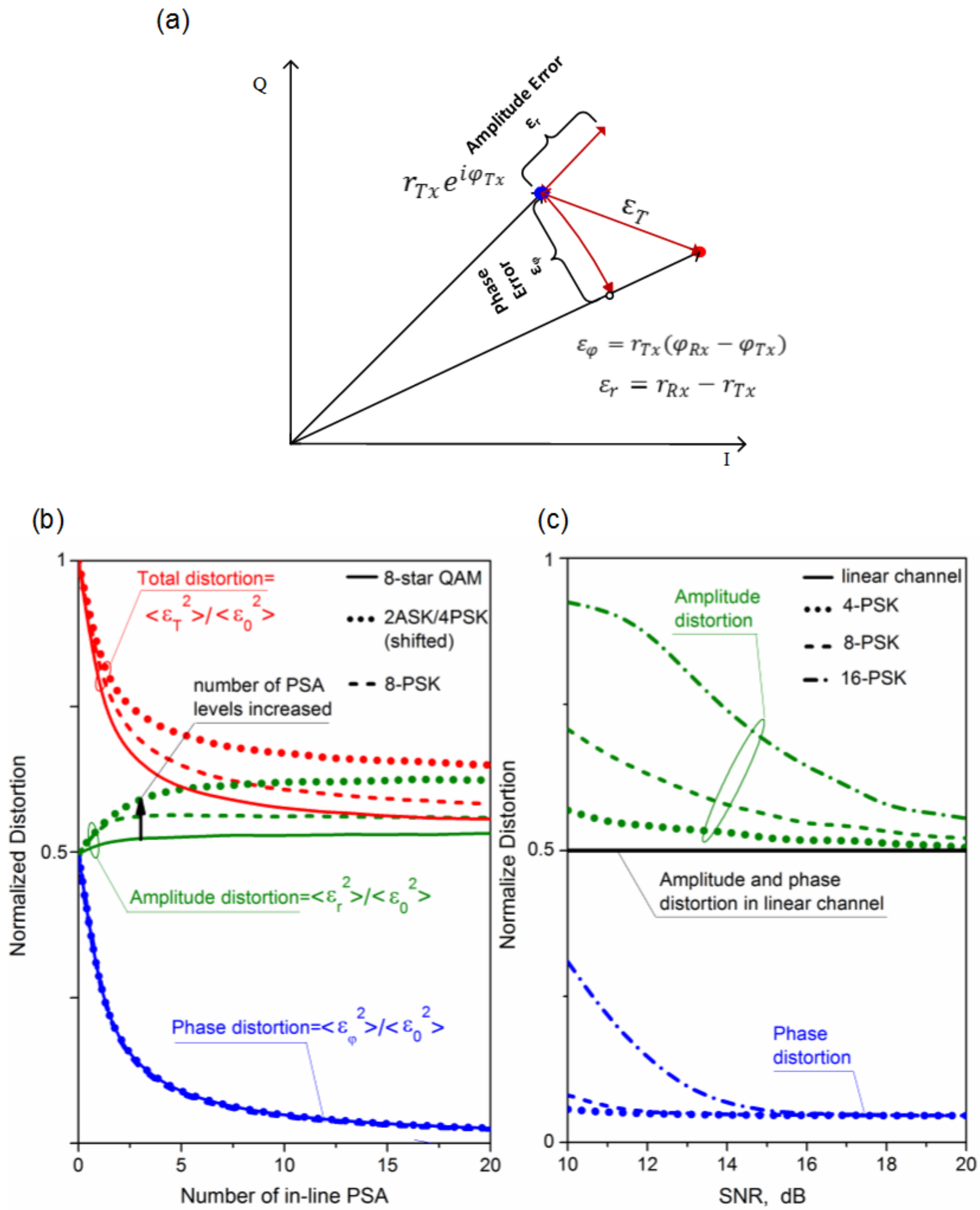

Fig. 5. (a) Definition of amplitude and phase error for the received signal. Phase, amplitude and total distortion of the output constellation (b) as a function of the number of in-line regenerators for the fixed value SNR=15 dB and (c) as a function of the SNR for 10 cascaded regenerators.

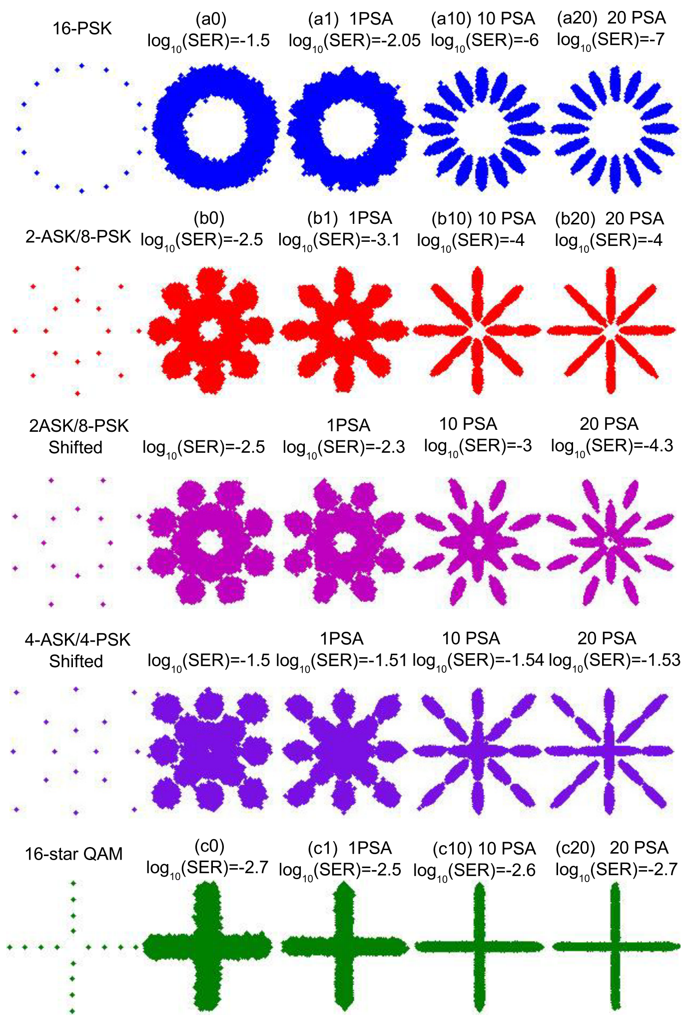

Fig. 6. Phase symmetric constellations formats for 16 symbols before (leftmost) and after transmission in linear channels (index 0) and nonlinear regenerative channel with cascaded 1, 10, 20 phase regenerators (indexes 1,10, and 20 respectively) for the fixed value SNR=18 dB.

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

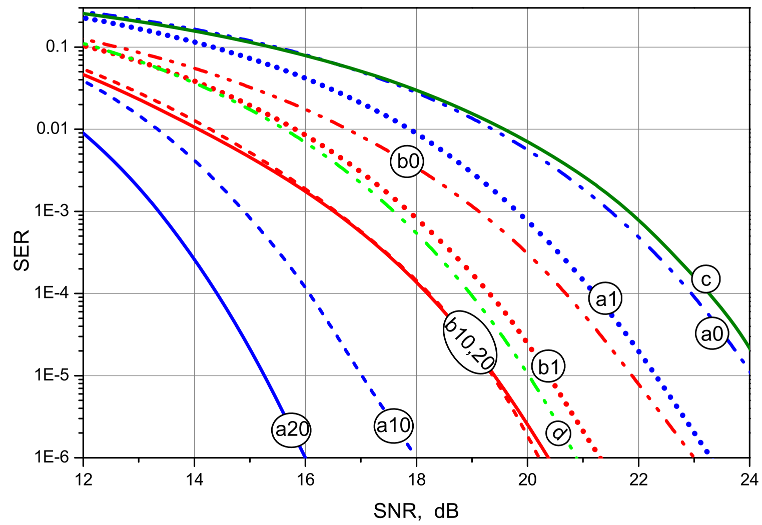

Fig. 7. The SERs as a function of SNR for the various types of modulation formats shown in Fig. 6, 1 amplitude level: 16-PSK (index a), 2 amplitude levels: 2-ASK/8-PSK (index b), and 4 amplitude levels: 16-star QAM (index c) for linear channel (index 0) and nonlinear regenerative channels with cascaded 1, 10, 20 phase regenerators (indexes 1, 10 and 20 respectively). Formats are also identified by line color, whilst the number of regenerators in the link is identified by the dashing of the line (dash length increases with number of regenerators). The SER of unregenerated 16-QAM format is shown for reference(index d).

transmission line. Figure 5(a) shows how the errors in amplitude ε_r and phase ε_φ were defined with respect to the individual error vectors ε_T. Figures 5(b) and 5(c) depict the total, amplitude and phase distortions, normalized to the total accumulated noise power of the linear system $< |\varepsilon_0|^2 >$. The normalization factor is independent on the type of modulation format and is a function of SNR only. Therefore, it allows to make fair comparison of the distortion in the units of the linear system (in the linear system the normalized total distortion is unity and phase and amplitude distortions are equal to 0.5). Furthermore, due to the modulation independency it provides a reference for comparing different modulation formats. In Fig. (5b) the transmission link was characterized by a fixed SNR of 15 dB. Note, that for large SNR values, when the phase noise is small so that the phase distortion is occurred within the plateau area, increasing the number of in-line regenerators reduces the accumulated phase distortion at the end of the link equally for each of the examined formats. However, for lower SNRs values, signals with lower number of phase states are expected to outperform as they will experience a more effective suppression of their phase noise from the corresponding PSA transfer function. This is demonstrated in Fig. 5(c), where the normalized distortion (in green the amplitude distortion and in blue the phase distortion) has been calculated for signals of different PSK order as a function of the SNR at the end of a line with 10 cascaded regenerators. The influence of the PSA transfer function on the accumulation of the amplitude noise is also depicted in Figs. 5(b) and 5(c). Due to the PSA induced phase-to-amplitude conversion an increase of the amplitude distortion is observed at the end of the line, which is different for each constellation. Specifically, 8-star QAM signals experience the least amplitude noise enhancement, as they are processed by 4-level PSAs that are more robust to this effect, compared to the other two cases (2-ASK/4-ASK, 8-PSK), which require PSAs of 8-levels. Furthermore, since the nonlinear transformation

#198945 - $15.00 USD Received 9 Oct 2013; revised 23 Nov 2013; accepted 4 Dec 2013; published 11 Dec 2013

induces a mixing of signal and noise, the phase-to-amplitude noise is additionally enhanced for two amplitude level signals compared to the PSK formats with the same average energy, see Fig. 5(c). However, the enhancement is incremental and saturates to a constant value as the number of regenerators is increased.

Finally, we have extended the analysis to modulation formats of higher complexity by considering 16-symbol constellations of different geometry and evaluating their performance in systems of cascaded phase regenerators. The performance of the single ring 16-PSK constellation has been benchmarked against the dual ring diagrams of 2-ASK/8-PSK and 2-ASK/8-PSK shifted, the four-ring 4-ASK/4-PSK shifted format, and finally the 16-star QAM. Figure 6 depicts the corresponding constellation diagrams at the input of the link, as well as, at the receiver after different numbers of cascaded regenerators. For the formats presented here, the effects of phase regeneration discussed above become more pronounced, in particular the trade-off between the efficiency of phase squeezing and the impact of phase-to-amplitude conversion.

The SER performance as a function of the SNR of the 16 point constellations of Fig. 6 is depicted in Fig. 7. Though amplitude modulated formats surpass densely-packed PSK for linear transmission, as the number of PSAs increases the SER associated with 16-PSK is gradually improved, and eventually the 16-PSK outperforms all other examined formats. Therefore, PSK signal modulation proves to be the most beneficial for transmission in PSA based regenerative links as it experiences the best SER improvement. As with the 8-symbol example, this is attributed to the intrinsic robustness of the PSK format against the amplitude noise, whereas, the multi-ring constellations are more vulnerable to this effect. Applying phase shift on the different rings of the constellations does not bring major improvement in their SER performance.

4. Conclusions

We have investigated the transmission performance of non-linear regenerative channels based on cascaded PSAs and we have explored the impact of the phase and amplitude noise accumulation mechanisms in the selection of the optimum modulation format. The results demonstrate that densely packed PSK formats are highly favored by the phase squeezing properties of the channel for high capacity transmission. On the other hand, the use of multi-amplitude level ring constellations brings minor improvements in SER performance as the benefits of phase regeneration are counterbalanced by the enhancement of the amplitude noise imposed by the phase to amplitude conversion in the PSAs. In particular, we find that the use of PSA regeneration with a 16-PSK signal outperforms the linear transmission performance of the 8-QAM system by 2 orders of magnitude in SER at an SNR of 16dB, suggesting that a system employing phase regenerators has the potential to offer higher point to point capacities than conventional dual quadrature transmission systems. We anticipate that the addition of a small level of amplitude regeneration to resist the phase to amplitude noise conversion process will further enhance the performance of the regenerative channel with respect to the conventional nonlinear channel.

Acknowledgments

The work has been supported by the EPSRC project UNLOC (Unlocking the capacity of optical communications), the Marie Currie - IEF project ARTISTE (Advanced regenerator technologies for high capacity systems), the Royal Society (Grant WM120035-TEST) and the EU-ICT project FOX-C (Flexible Optical Cross-connect Nodes enabling next generation flexible optical networking).