Effect of All-Optical Phase Regeneration on Fiber Transmission Capacity

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ABSTRACT
We investigate theoretically the benefits of using all-optical phase regeneration in a long-haul fiber optic link. We simulate numerically the bit-error rate of a WDM optical communication system over many fiber spans with periodic re-amplification and compare the results obtained with and without the use of a phase regenerator at half the transmission distance. Our results suggest that, depending on the modulation format, a significantly improved performance by up to 1.5 orders of magnitude can be achieved.

Keywords: Optical communication; Phase regeneration; Fiber capacity; All-optical signal processing.

1. INTRODUCTION

All-optical phase regeneration of fiber optic communication signals reduces the impact of phase noise, induced by, e.g., amplified spontaneous emission in the amplifiers or nonlinear self/cross-phase modulation of the phase shift keyed (PSK) symbols during transmission. By regenerating at a distance prior to which few or no errors have occurred, the phase regenerated signal can subsequently be transmitted further for the same bit error ratio (BER). All-optical phase regeneration has been demonstrated for 2 [1,2] and 4 [3-5] phase levels and in principle can be extended to higher level phase shift keying formats [3,5] where greater spectral efficiency is offered. At high bit rates optical regeneration has the potential to work faster and consume less power than electronic compensation and its fiber-to-fiber nature offers simple network integration.

While the transfer function introduced in Refs. [3-5] is excellent at squeezing phases to desired constellation points, it suffers notable phase-to-amplitude noise conversion. Additional amplitude noise is undesirable as it can be converted back into phase noise during subsequent propagation and it is not yet clear how much impact this has. Quite often optical regeneration is demonstrated when phase noise is much greater than amplitude noise; in some experiments the noise is artificially created and its distribution biased to supply more phase noise than amplitude noise [2,4]. Such noise distributions are useful for demonstration purposes but are not realistic representations of noise in modern-day fiber communications when wavelength-division multiplexing (WDM) is employed [6]. With multiple channels and multiple sources of noise the distributions often appear almost Gaussian and the amplitude and phase noise contributions are comparable [7] even at 10 Gbit/s where channel crosstalk might be expected to be lower than at 40 Gbit/s. It is thus imperative that optical regeneration is demonstrated in a state-of-the-art communications scenario if it is to be championed as viable. Herein a realistic performance characterization in a WDM system is presented showing existing optical phase regeneration designs can indeed reduce bit error ratios by more than an order of magnitude.

2. ALL-OPTICAL PHASE REGENERATION

Here we achieve optical regeneration following Kakande et al. [3]. Regeneration of a single carrier frequency M-phase level signal is achieved by judiciously combining the signal with an M-1 phase harmonic using four-wave mixing (FWM) in a highly nonlinear fiber (HNLF) section. The signal enters the HNLF together with two pumps, one detuned in frequency by $-\Delta f$ relative to the signal and the other at $M\Delta f$ (Fig.1 a). At first, FWM generates cascaded harmonics at integer multiples of the frequency difference, with each harmonic carrying an integer multiple of the signal phase due to phase matching. Eventually the $(M-1)$ harmonic grows sufficiently large that non-degenerate FWM between the two pumps, the harmonic and the signal combines the harmonic with the signal realizing a staircase in the signal phase transfer function (Fig.1 b, top). The step function maps all input phase samples falling within the width of the step to a single output phase, the height of the step; albeit at the expense of some variation in amplitude (Fig.1 b, bottom). By adjusting the pump powers we optimize the weight m of the harmonic in the following signal transfer function of the HNLF:

$$A_{out}e^{i\phi_{out}} \propto e^{i\phi_{in}} + me^{-i(M-1)\phi_{in}}, \tag{1}$$

where A, ϕ and M are the signal amplitude, phase and integer phase quantization level respectively. To decide the optimal value for m the optimization process in Ref. [5] was used as a guide and fine adjustments were made accordingly following trial runs. Fig. 1 c) shows a noisy signal constellation diagram (in-phase and quadrature components) before and after all-optical phase regeneration; the phase noise has been reduced at the expense of a small increase in amplitude noise.

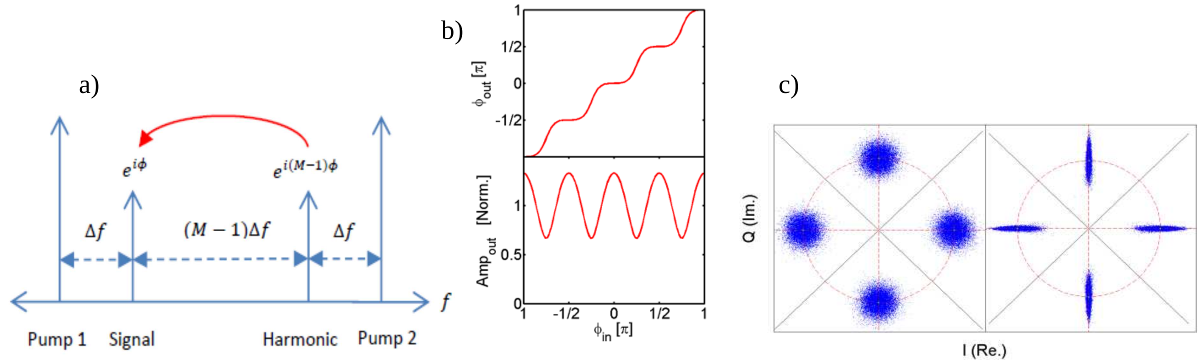

Fig. 1: a) Spectral setup shows FWM combing the harmonic and signal. b) The output phase and amplitude signal transfer through the HNLF as a function of input phase. c) The phase regeneration of a noisy QPSK signal (in-phase and quadrature components).

3. FIBER CAPACITY SIMULATIONS

A generalized nonlinear Schrödinger equation [8] incorporating nonlinear and dispersive interactions was solved numerically using a split-step Fourier method to simulate propagation over long-haul distances. Gaussian pulses modulated with Gray-coded 4 (8) PSK data, were frequency multiplexed over 39 (23) channels separated by $135\ (175)\ \text{GHz}$ about a central wavelength of $\lambda = 1555.6\ \text{nm}$, with a pulse repetition rate of $20\ (13.33)\ \text{GHz}$ giving a channel bit-rate of $40\ \text{Gbits/s}$. Once constructed, each channel was narrowly filtered at the transmitter using a super-Gaussian filter to isolate the central spectral lobe. While this introduces some inter-symbol interference it ultimately reduces the bit-error rate when the same narrow filter is used to de-multiplex before the regenerator and again at the receiver. This is mainly because it reduces power in low signal-to-noise ratio spectral regions allowing an increase in total average power and improved signal-to-noise ratio. For transmission, a standard single-mode communications fiber was used with single span length $L = 100$ km, nonlinear coefficient $\gamma = 1.3\ \text{W}^{-1}\text{km}^{-1}$, dispersion $D = 16.18$ ps/(km.nm) at $\lambda = 1555.6$ nm, dispersion slope $S = -41.55\ \text{ps/(km. nm}^2)$ and loss $\alpha = 0.18\ \text{dB/km}$. After each span the average peak power was restored using amplification with a 3 dB noise figure.

In various examples the phase regenerative section was simulated in full by propagating the pumps and a single frequency signal in a HNLF with length $L = 302$ m, nonlinear coefficient $\gamma = 11\ \text{W}^{-1}\text{km}^{-1}$, dispersion $D = -0.8$ ps/(km.nm) at $\lambda = 1555.6$ nm, dispersion slope $S = 0.018\ \text{ps/(km. nm}^2)$ and loss $\alpha = 0.2\ \text{dB/km}$. Once the correct tuning of pump powers was achieved however, the result was indistinguishable from that achieved simply by using the analytic transfer function. Consequently to save computation time the analytic transfer function (1) was used in bit error ratio tests. At the mid-link point the individual frequency channels were isolated and analytically regenerated and then recombined for further propagation. After simulating the remaining transmission distance electronic dispersion compensation was performed before frequency de-multiplexing, sampling and mean phase error correction. The phase samples were then converted into binary numbers and the bit errors counted.

4. SIMULATION RESULTS

To calculate the bit error ratio $2^7 = 128$ symbols were propagated in each of the channels and each simulation was repeated 20 times using different random input sequences. Consequently, combining all the data meant a single error corresponded to a bit error ratio of $\sim 1 \times 10^{-5}$ in both 4 and 8-PSK formats, which is to be compared with the 1×10^{-3} bit error ratio required to enable forward error correction (FEC). Using a supercomputer the simulations were also repeated while sweeping peak signal power.

4.1 QPSK

After propagating QPSK (i.e. 4-PSK) data over $2700\ \text{km}$, the bit error ratio was measured as a function of average input peak power (Fig.2 a). We compared the effect of filtering and recombining the channels at 1300 km having bypassed the phase regenerator, with filtering and phase regenerating at 1300 km. Without regeneration the bit error rate approaches the 1×10^{-3} FEC limit at the end of the link with a minimum BER of 0.69×10^{-3} at optimal input peak power -1.9 dBm. Regenerating reduces the minimum BER to 0.13×10^{-3} at -1.4 dBm. In the QPSK format there is a large amount of amplitude noise accompanying the phase noise and the former remains uncorrected. Consequently, this amplitude noise is subsequently converted into phase noise during propagation and limits successful regeneration. The phase regenerator design itself can also push large phase deviations to low amplitude, relative to the mean, where symbols subsequently suffer worse signal-to-noise ratio and where they are easily phase modulated by the symbols pushed to high power, nonetheless an overall improvement remains. Note that the distorted shape of the noise distribution demonstrates the need for counting bit errors rather than fitting Gaussian distributions when using such a phase regenerator.

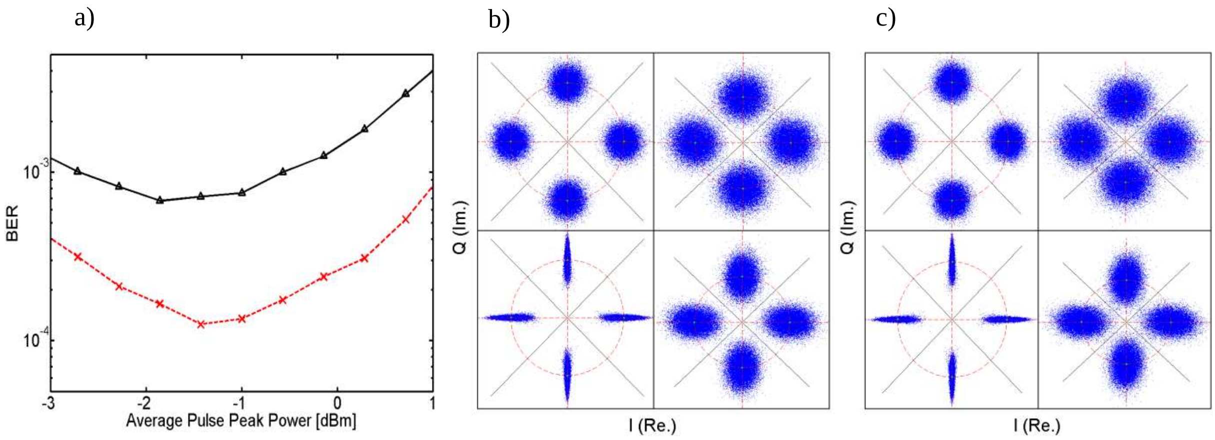

Fig. 2: a) QPSK bit error ratio at 2700 km as a function of input power without (black solid line, triangles) and with regeneration at 1300 km (red dashed line, crosses). b), c) Constellation diagrams mid-link (left column) and at the end (right column), without (top row) and with (bottom row) phase regeneration once at 1300 km for input peak powers b) -1.4 dBm, c) 1 dBm; the left column is also indicative of before (top) and after (bottom) regeneration.

4.2 8-PSK

For comparison, we also simulated 8-PSK data sent over 2000 km. Again the BER was measured as a function of average input peak power (Fig.3 a). The 8-PSK format is less robust to noise than QPSK which reduces the propagation distance for a fixed BER. Without regeneration the BER approaches the 1×10^{-3} FEC limit at the end of the link with a minimum BER of 0.56×10^{-3} at optimal input peak power 0.43 dBm. Regenerating once at 1000 km reduces the minimum BER to 0.18×10^{-4} at -0.43 dBm. Phase regeneration has had more of an impact in this format as phase noise really does dominate here. Also, there is a slight reduction of phase-to-amplitude noise conversion in higher M-PSK formats as the harmonic weight m required to achieve the optimal phase transfer function, Eq. (1), decreases and, once again, with smaller m the amplitude variation reduces. Conversely, the step of the phase transfer function also reduces slightly for higher M which hinders the regeneration of large phase errors. However, overall it seems the benefits of reduced amplitude variation and operating in a regime dominated by phase noise enable phase regeneration to have more of an impact in 8-PSK than in QPSK.

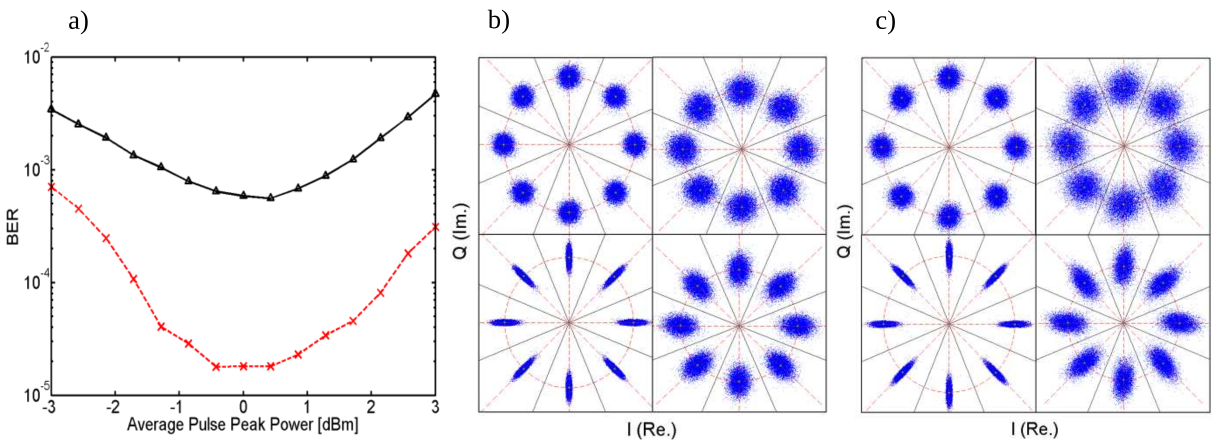

Fig. 3: a) 8-PSK bit error ratio as a function of input power at a distance of 2000 km, without (black solid line, triangles) and with regeneration at 1000 km (red dashed line, crosses). b), c) Constellation diagrams mid-link (left column) and at the end (right column), without (top row) and with (bottom row) phase regeneration for input powers b) 0 dBm, c) 3 dBm; the left column is also indicative of before (top) and after (bottom) regeneration.

5. CONCLUSIONS

We have demonstrated that all-optical phase regeneration is capable of reducing the bit-error ratio of 8-PSK signals by 1.5 orders of magnitude but that results in QPSK are less impressive with a bit error ratio reduction of half an order of magnitude reported. Phase regeneration has more of an impact in 8-PSK than in QPSK because phase noise is more dominant in 8-PSK while QPSK also suffers substantial amplitude noise which is uncorrected and converts into phase noise. Results might be improved if phase-to-amplitude noise conversion could be reduced during regeneration.

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