Efficiency of regenerative schemes

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ABSTRACT

We explore the efficiency of various regeneration schemes in communication systems. We discuss new efficient schemes for multilevel phase and amplitude regeneration and illustrate it on example of 16-symbol constellations.

Keywords: all-optical regeneration, nonlinear optical loop mirror, phase sensitive amplification.

1. INTRODUCTION

To increase information transmission rate one needs to operate with advanced multi-level modulation formats, which are sensitive to transmission distortions. All-optical signal regeneration is an attractive method to mitigate noise and nonlinear signal distortion [1-5]. A number of schemes have been proposed to achieve phase [6-8] or amplitude [9-12] noise suppression. Placed in cascades such elements enable to improve signal transmission effectively [2-3, 8]. Recently, a combined scheme [12] for simultaneous regeneration of phase and amplitude was demonstrated by combination of nonlinear optical loop mirror and phase-quantizer based on phase sensitive amplifier (PSA). However, to enable high capacity transmission regenerators are expected to handle higher order formats, whereas currently known schemes enable only two-level amplitude regeneration [9-10], whereas employing dual-stage phase quantizer is highly challenging [13].

Here we study the performance of multilevel regenerative scheme – the regenerative Fourier transform (RFT) [14], which enables suppression of amplitude and phase noise. To take full advantage of regeneration in coherent optical communications it is necessary to adjust modulation formats to the properties of nonlinear regenerative elements. Here we use a technique of regenerative mapping (being general, simple, and analytical) providing an effective solution for design of multilevel regenerative schemes. We estimate the efficiency of the model with existing multilevel phase-quantizer based on PSA [6-8].

2. REGENERATIVE MAPPING

Here a "regenerator" is a device that creates a smooth nonlinear transfer function (TF), which asserts attractive regions around the alphabet – a set of points used for signal modulation. Regeneration is a type of constructive nonlinearity, where a nonlinear transfer function and signal modulation should be mutually adjusted, so that the alphabet points are not changed, whereas the distorted points are attracted to the closest alphabet point.

Therefore, the alphabet points are required [5, 14-15] to be stationary $T(x^*) = x^*$ and stable $|T'(x^*)| \leq 1$. Finally, the optimum positioning of the alphabet point is in the center of the attraction region $T''(x^*) = 0$. These three simple analytical requirements define a regenerative mapping – a technique that can be applied to any system to achieve simultaneous optimization of the alphabet and nonlinearity. The procedure is of particular importance for developing multilevel regenerative systems. Also, as cascadability plays crucial role in regeneration, non-optimized cascaded devices can degrade signal transmission. Therefore, optimization is a necessary part of any regenerative system design. Further, we demonstrate the application of the method on known multilevel amplitude and phase regenerative models.

2.1 PHASE REGENERATION

We start with a well-known scheme for phase regeneration based on phase sensitive amplifiers (PSA). The nonlinear TF for M-level PSA [6-8] is given by:

$$r_{out} e^{i\phi_{out}} = r_{in} e^{i\phi_{in}} \left(1 + m e^{-i\phi_{in} M}\right) \tag{1}$$

Here, and ϕ_{out}=$F(\phi_{in})$ is the staircase phase response (see Fig. 1a), which can be explicitly written as:

$$\phi_{out} = \tan^{-1}\left(\frac{\sin[\phi_{in}] + m\sin[\phi_{in}(1-M)]}{\cos[\phi_{in}] + m\cos[\phi_{in}(1-M)]}\right) \tag{2}$$

whereas, r_{out} is the output amplitude of the regenerator, characterized by a sinusoidal dependence on the phase of the input signal (see Fig. 1b). Parameter m is an optimization parameter, which governs the regenerative properties of the device.

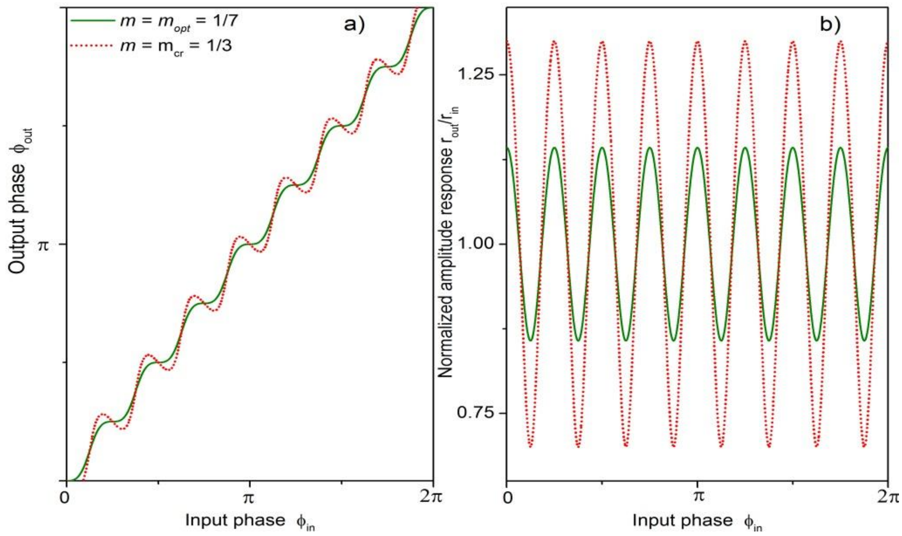

Figure 1. Transfer function of the 8 level PSA phase regenerator a) stair-case response of the output phase and b) sinusoidal amplitude response plotted as function of the input phase for different values of an optimization parameter m.

The scheme can be practically realized by coherent addition of an input signal and its $M-1$ order phase conjugated harmonic. In the considered system the alphabet is defined by the stationary inflection points (i.e. the center of the attraction regions): $F''(\varphi^*) = 0$, this defines the alphabet points to be determined by the order of the PSA: $\varphi^* = l\pi/M,\ l \in Z$. Finally, the stability condition (i.e. the distortion of the output signal expected to be suppressed) leads to: $|F'(\varphi^*)| \leq 1$. Calculated at the alphabet points it gives the operating margins of the PSA and the optimum parameter value is defined by equality: $F'(\varphi^*) = 0$, which leads to $|m_{opt}| = \frac{1}{M-1}$. This case is further referred as super-stable and it results in the plateau regions around the alphabet points.

2.2 REGENERATIVE FOURIER TRANSFORM

RFT is the first order of a Fourier expansion for the ideal stepwise transfer function (TF): $y = x + \alpha \sin(\beta x)$, where α and β are RFT parameters. The RFT can be implemented by using a scheme presented in the Supplemental materials of [14]. The corresponding TF with multiple equidistant plateaus is plotted in Fig. 2. One can apply the regenerative mapping technique to optimize the TF and adapt it to the given signal modulation format (alphabet), which gives the optimum parameters relation: $\alpha\beta = 1$. Further, alphabet is determined as the set of stationary and stable points placed in the center of the corresponding plateaus: $x_k^* = \frac{(2k+1)\pi}{\beta},\ k \in \mathbb{Z}$.

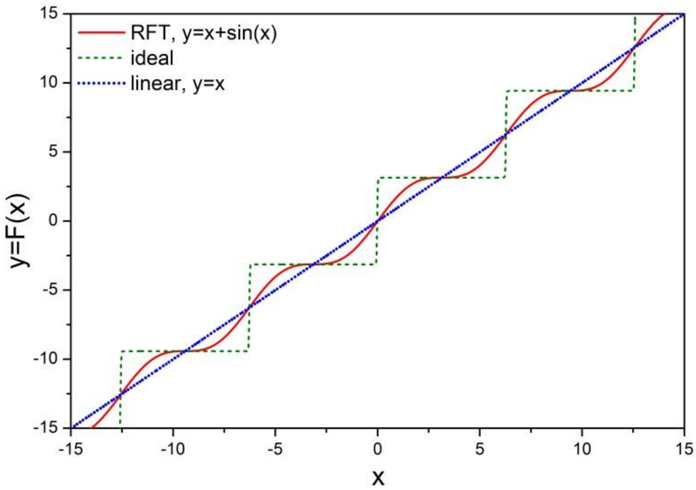

Figure 2. Transfer function of the RFT is plotted by red solid lines, the corresponding transfer function of the ideal regenerator is plotted alongside by green dashed line.

The RFT can be applied to both signal quadratures to achieve periodic plateaus around the alphabet points with the closest approximation of the ideal TF. Thus, it is efficient regenerative model which operates on conventional rectangular modulation formats with high number of levels without hard decision requirement.

3. NUMERICAL SIMULATIONS

Here we compare the regenerative performance of multilevel regenerative systems: phase quantizer based on PSA and the regenerative Fourier transform. An optimum constellation is defined by regenerative TF and number of elements in cascade. Here we consider 16-symbolconstellations adapted to the particular regenerative scheme: 16 phase shift keying (PSK) and rectangular quadrature amplitude modulation (QAM) for 16-level PSA and RFT correspondingly. We modelled numerically signal transmission through a cascade of equidistant regenerative elements. Noise was modeled as a uniformly distributed additive white Gaussian noise added linearly along the transmission line after each transformation (destructive nonlinearity during transmission was neglected). We characterize the system by the signal-to-noise ratio (SNR) defined as the ratio of the input signal power to the power of the linearly added noise accumulated along the link, thus coinciding with the SNR of the equivalent linear system (in the absence of regeneration). To characterize the efficiency of noise suppression we calculated a symbol error rate (SER) by direct error counting of simulated equiprobable $\mathbf{2^{25}}$ symbols as a function of the SNR. One can see the improvement in SER due to cascaded regeneration in Fig. 3. Moreover, one can compare the efficiency of regenerative different schemes to the improvement given by the ideal regenerator. By comparing the resulted SERs one can estimate the signal improvement due regeneration. We show that for high order constellation the simultaneous regeneration of both phase and amplitude is required (see Fig. 3a), compare to regeneration of phase only (Fig. 3b).

Thus, we have demonstrated that the RFT enables efficient signal regeneration in both phase and amplitude and the signal transmission (estimated by SER) is highly improved compared to existing multilevel PSA-based phase-quantizer.

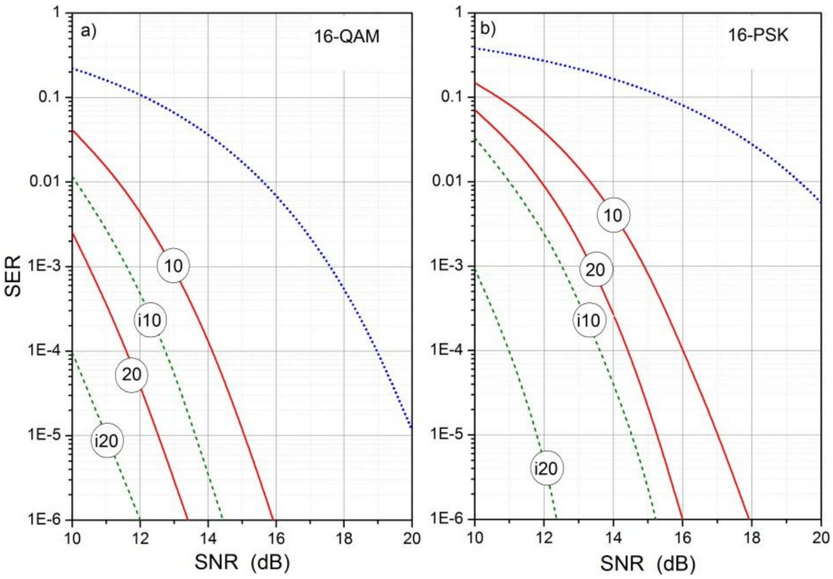

Figure 3. SERs as a function of SNR for 16-QAM with a different number (placed in circles for each curve) of a) RFT filters with the TF: $y_{R,I} = x_{R,I} + \sin(x_{R,I})$ and b) 16-level PSA are shown by red solid curves. The SER of the corresponding system with the ideal regenerators are plotted by greed dashed curves (denoted by symbol i) and the SERs of the linear channel are shown for comparison by blue dotted lines.

4. CONCLUSIONS

We have investigated the design of multilevel regenerative schemes with the emphasis on system optimization. The developed regenerative mapping technique enables simultaneous optimization of both signal modulation and regenerative element. The method is a necessary part of a regenerative system design and it can be applied to various regenerative model. The effect of cascadability on system optimization was illustrated. Effective phase and amplitude regenerative scheme was demonstrated and the performance was illustrated on cascaded transmission of 16-QAM.

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