TRIAL OF NONLINEAR TOLERANT SUPER-GAUSSIAN DISTRIBUTION FOR PROBABILISTICALLY SHAPED MODULATION

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Abstract: Probabilistically-shaped constellations are found to have larger than expected Kerr nonlinearity induced penalty in long-haul transmission. In this paper, the field-trial for the nonlinear tolerant super-gaussian distribution is demonstrated for probabilistic shaped constellations with various spectral efficiencies. The experimental results show a significant improvement.

1. INTRODUCTION

In recent years, two important techniques emerged that have shown significant promise in achieving higher capacity or higher spectral efficiency (SE) for a given signal to noise ratio in the channel. Alternatively, these techniques can improve signal to noise ratio (SNR) tolerance at a given SE. These techniques are geometric shaping (GS) and probabilistic shaping (PS). In geometric shaping, the position of constellation points is optimized to reach higher SE or more tolerance to the fiber nonlinearity, while in probabilistic shaping the constellation points are on a uniform grid but with different probabilities at each point. Both techniques can reach up to 1.53dB improvement in SNR tolerance asymptotically for the Gaussian channel. These two methods have gained significant attention in coherent optical communication systems [1].

Probabilistic shaping is attractive because the net system SE can be adjusted very finely over a wide range by just changing the probabilities of each transmitted symbol from a regular square QAM constellation set using a distribution matcher [3], meanwhile the underlying processing engine in the forward error correction (FEC) and digital signal processing (DSP) remains the same. In probabilistic shaping the labeling of the constellation points can use Gray code which gives best achievable performance for bit-wise decoders.

Although PS modulation outperforms regular equiprobable QAM modulation in the linear regime, when propagated over long distances of fiber, the accumulated Kerr nonlinearity is more profound in PS modulation versus regular QAM modulation [4]. This nonlinear effect can significantly offset the shaping gain obtained in the linear regime. The main reason for this degradation is that the Maxwell-Boltzmann distribution for the constellation points is optimized for linear Additive White Gaussian Noise (AWGN) channel. For long-haul fiber transmission this assumption is not entirely valid and the environment at optimum launch power can have a significant non-linear component. In this case there should be other considerations, such as the non-linear parameters of fiber, applied to optimize the distribution of the points. In [2], a novel super-Gaussian distribution is proposed that can outperform the Maxwell-Boltzman distribution when subjected to long distance fiber transmission. In this paper, a field trial for this algorithm has been performed and demonstrates significant improvement compare to Maxwell-Boltzman distribution.

2. PROBLEM DEFINITION

After propagating long distances, the signal in the fiber accumulates both amplified spontaneous emission (ASE) noise and nonlinear noise. For dual-polarization transmission and adopting the approach in [4], the effective SNR of the channel is given by:

$$\mathrm{SNR}_{\mathrm{eff}} = \frac{P_{tx}}{\sigma_{\mathrm{eff}}^2} = \frac{P_{tx}}{\sigma_{ASE}^2 + \sigma_{NLI}^2} \quad (1)$$

P_{tx} is the optical launch power, σ_{ASE}^2 is the noise variance of the ASE noise from optical amplifiers and σ_{NLI}^2 is the Non-Linear Interference (NLI) variance that includes both intra- and inter-channel nonlinear distortions. σ_{eff}^2 is [5]:

$$\sigma_{\mathrm{eff}}^2 = \sigma_{ASE}^2 + \sigma_{NLI}^2 = \sigma_{ASE}^2 + P_{tx}^3\chi_0 + P_{tx}^3[(\hat{\mu}_4 - 2)\chi_4 + (\hat{\mu}_4 - 2)^2\chi_4' + \hat{\mu}_6\chi_6] \quad (2)$$

where $\hat{\mu}_4$ and $\hat{\mu}_6$ are the standardized moments of the channel input X and χ_0, χ_4, χ_4', and χ_6 are real coefficients that represent the contributions of the fiber nonlinearities.

The well-known Maxwell-Boltzmann distribution has been used to characterize the distribution of X, and this has been proven to maximize capacity in the AWGN channel [6]. The idea for the super-gaussian distribution is that if we substitute the exponent power 2 in Maxwell-Boltzmann distribution [2] with a parameter P, we have a general form of a super-Gaussian distribution.

$$p(x) = e^{-\lambda x^P} / Z(\lambda) \quad ,\lambda \geq 0 \quad (4)$$

The advantage of the super-gaussian distribution is that by modifying P, we can significantly reduce the $\hat{\mu}_4$ and $\hat{\mu}_6$ of the signal X, thereby increasing nonlinear tolerance when propagating over long fibers. In Table 1 below, we compare the $\hat{\mu}_4$ and $\hat{\mu}_6$ of Star-8QAM, PS-64QAM with Maxwell-Boltzmann distribution ($P = 2$, $\lambda = 0.11$, $\mathrm{SE} = 6$ b/s/Hz) and PS-64QAM with super-Gaussian distribution ($P = 3.5$, $\lambda = 0.17$, $\mathrm{SE} = 6$ b/s/Hz). All three modulations shown in the table have the same SE.

Modulation format	$\hat{\mu}_4$	$\hat{\mu}_6$
PS-64QAM, $P = 2$, $\lambda = 0.11$	2	6
PS-64QAM, $P = 3.5$, $\lambda = 0.17$	1.61	3.29
Star-8QAM	1.36	2

Table. 1: 4th and 6th standardized moments of PS, SE=3 b/s/Hz and regular modulation

As it is shown, the $\hat{\mu}_4$ and $\hat{\mu}_6$ of the PS modulation with super-Gaussian distribution ($P = 3.5$) is significantly decreased compared to the Maxwell-Boltzmann distribution and it improves the performance of the PS modulation at optimum launch power.

3. EXPERIMENT RESULTS

The experiment was carried out using a recirculating loop with span length of 70 km and TeraWave fiber. The total distance is ~4000 km and uncompensated. 36 waves are bulk modulated using two sets of coherent dual-polarization transmitters. For high spectral efficiency, the waves are multiplexed at 6% excess BW factor. Each wave is constructed by digitally multiplexing four 8.2 Gbaud subcarriers with excess BW factor of 6%. The composite signal has electrical singled sided BW of about 17 GHz. The four XI, XQ, YI, YQ RF signals at the output of four high speed 64 GS/s DACs are driven into off-the-shelf dual-polarization MZ modulators. In the receiver off-the-shelf coherent receivers are used together with high speed sampling scope. The captured data is post-processed using sophisticated DSP algorithms such as equalizer training using known symbols, and feed-forward carrier recovery using a blind phase search algorithm. Figures 1 & 2 plot the measured relative Q versus launch power for different exponent P values. In Figure 1, the best performance for 6 Bit per Polarization muxed Symbols (BPS=6 bits) in the experiment would be at P = 4. It is shown that super-Gaussian distribution for PS-64QAM can have 0.25 dB Q gain at optimum launch power compared to a Maxwell-Boltzmann distribution. In Figure 2, the best performance for the BPS=7 bits, would be at P=3, outperforming the Maxwell-Boltzmann distribution by 0.2 dB Q gain at optimum launch.

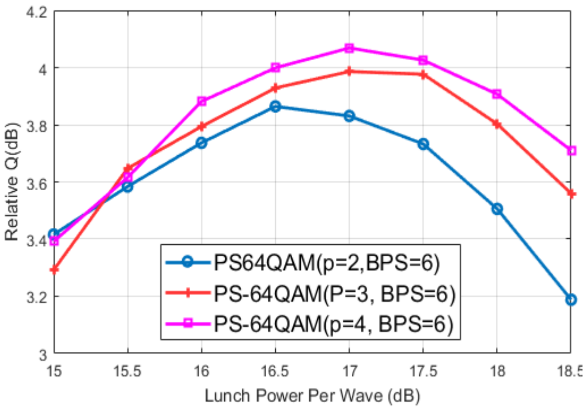

Figure 1: Measured super-Gaussian nonlinear performance for 4000 km of uncompensated Tera Wave fiber at PS-64QAM BPS=6 bits.

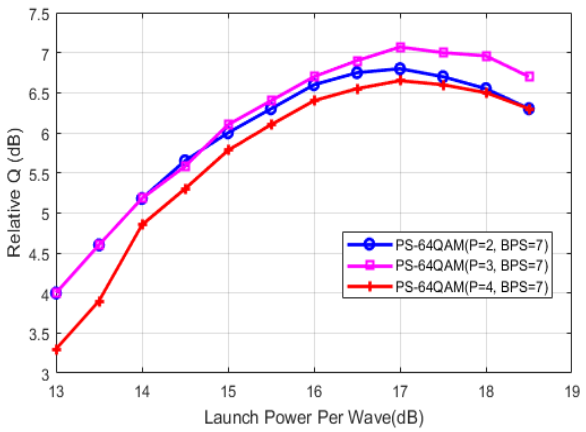

Figure 2: Measured super-Gaussian nonlinear performance for 4000 km of uncompensated Tera Wave fiber at PS-64QAM BPS =7 bits.

A field trial was performed on a legacy dispersion managed optical cable with a dispersion map shown in Figure 3 to test the nonlinear shaping performance. This cable contains a zero-dispersion window and the channel under test had a dispersion of -3200 ps/nm. The PS-64QAM channel under test was within a comb of carriers at 34.375 GHz spacing with BPS=5 bits.

Figure 4 shows a nonlinear Q gain of 0.1 dB on this legacy cable.

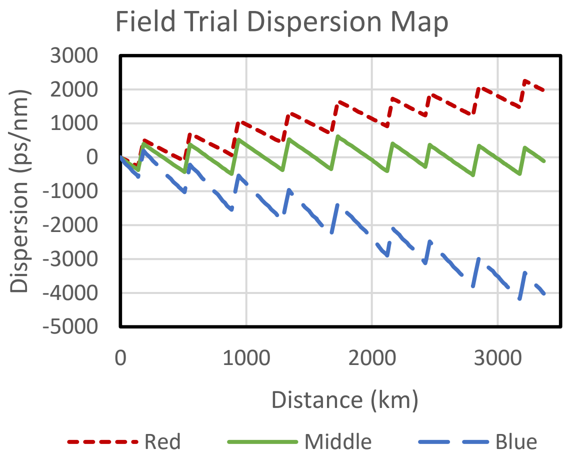

Figure 3: Field trial dispersion map contains a zero-dispersion window near the middle of the spectrum. The legacy cable impacts higher nonlinearity penalties to coherent carriers compared to newer cables with TeraWave fiber.

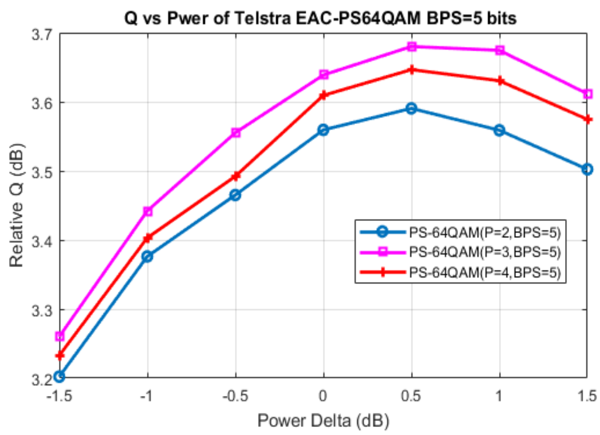

Figure 4: Measured super-Gaussian nonlinear performance for 3000 km of compensated Telstra fiber at PS-64QAM BPS=5 bits.

4. CONCLUSIONS

A super-Gaussian distribution has been

proposed which outperforms Maxwell-Boltzmann distribution for probabilistically shaped signals, particularly in systems with nonlinear transmission. Field-Trail results have shown that the super-gaussian distribution have higher nonlinear tolerance.

5. REFERENCES

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