Evolutionary Design of Pulse-Shaping FIR Filter to Mitigate Fiber Nonlinearity

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Abstract

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OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

The effect of pulse shaping in fiber-optic communications has been investigated in literature [1–9]. For example, it was shown [1–3] that reduced nonlinear interference (NLI) is achieved by using a return-to-zero (RZ) pulse. This is mainly because its wider spectrum can decrease coherence between neighboring frequency components along fiber propagation. Analogously, an impulsive Nyquist shape was designed numerically [4, 5]. To further improve performance in wavelength division multiplexing (WDM), stair-case pulse [6] and root M-shaped pulse (RMP) [7, 8] were proposed. It was verified [8] that the RMP performs better than the impulsive shape and root-raised-cosine (RRC) filter, leading to a reach extension by more than 11.7%. In this paper, we employ a meta-heuristic optimization method, called covariance matrix adaptation evolutionary strategy (CMA-ES) [10], to design a finite-impulse response (FIR) filter so that the NLI is minimized. We show that the optimized FIR filter can outperform RRC and RMP filters, by up to 0.23 dB, in dual polarization 16-ary quadrature-amplitude modulation (DP-16QAM) transmission.

2. FIR filter design

A block diagram of the simulated system is shown in Fig. 1. Three DP-16QAM channels at a baud rate of 34 GBd with 50 GHz spacing are multiplexed and propagated over multiple 80 km spans of standard single mode fiber (SSMF) without inline dispersion compensation, using an adaptive step-size Manakov model. We assume an attenuation of 0.2 dB/km, dispersion factor of $D = 17$ ps/nm/km, and nonlinearity factor of $\gamma = 1.2$ /W/km. Fiber loss is compensated using an ideal Erbium-doped fiber amplifier every span. All amplified spontaneous emission (ASE) noise are applied just before the receiver assuming an amplifier noise figure of 5 dB. An ideal coherent optical receiver is used and bulk dispersion compensation is applied via frequency domain processing. A linear equalizer (LEQ) is used to compensate for any residual intersymbol interference (ISI). The taps for the LEQ are determined directly from the transmitting and receiving signals in a data-directed minimum mean-square error (MMSE) sense.

The taps for the FIR filter at the transmitter are optimized to maximize Q factor in nonlinear transmission. Note that the Nyquist condition is not required since LEQ is used at the receiver to deal with channel ISI. This relaxation may give us a potential to compete with the other Nyquist-based filters [4–8]. For a $(2L+1)$-tap symmetric FIR filter, we have at least L degrees of freedom to design. It is known that RMP filter requires relatively more taps than RRC does, to mitigate the truncation penalty [8]. However, in practice, we may not be able to use very long FIR filters; typically half filter length should be $L \leq 31$. Moreover, we cannot use a high oversampling factor. Hence, rather than optimizing its transfer function, it may be better to design finite tap coefficients under such hardware limitations.

We use CMA-ES [10] to optimize the tap coefficients. Fig. 2 shows the optimization trajectory across the evolution steps, where the RRC filter taps are used as the initial values, for 15 spans at a launch power of 1 dBm. For each optimization trial, CMA-ES modifies the FIR tap coefficients to maximize the Q factor, which is evaluated by transmission simulation given a randomly generated DP-16QAM sequence of 2^{14} symbols each iteration. It is observed from Fig. 2 that a few number of iterations offer more than 0.3 dB improvement. After 100 and 1000 iterations, improved FIR taps having significant gain of greater than 0.4 and 0.5 dB respectively can be found.

Fig. 3 shows the transfer functions of RRC, RMP, and optimized filters. As a benchmark, we use a depth factor of $\beta = 0.5$ for the RMP filter as its performance was well investigated [8]. The optimized filter show higher variation

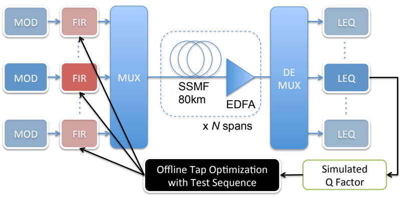


Fig. 1: Fiber-optic systems and offline evolutionary design of FIR filter to maximize the Q factor, simulated with test sequence in advance.

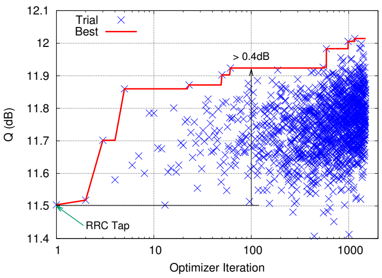


Fig. 2: FIR evolution trajectory via CMA-ES optimizer.

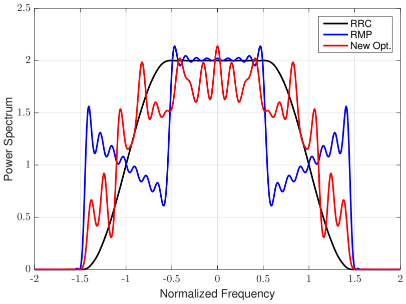
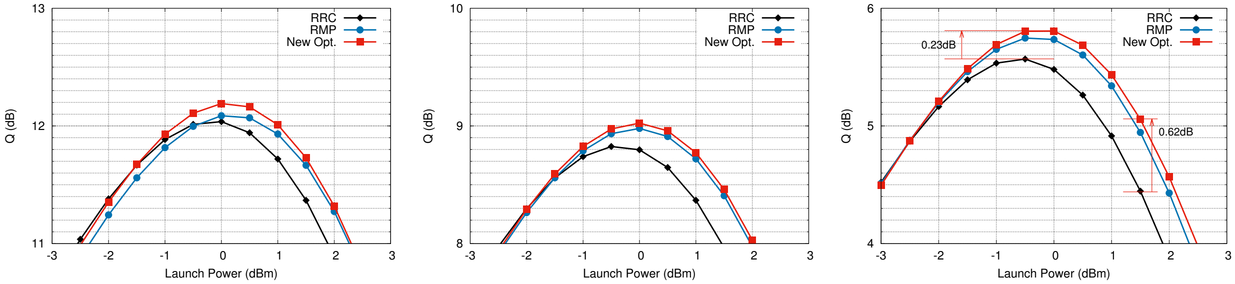


Fig. 3: RMP, RRC and optimized filter for $\alpha = 0.47$, $L = 31$ and $M = 2$.



(a) 15 spans: 1,200 km

(b) 30 spans: 2,400 km

(c) 60 spans: 4,800 km

Fig. 4: Nonlinear transmission performance of DP-16QAM in dispersion-unmanaged SSMF fiber links.

over the center frequency range compared to RMP and RRC and roughly follow the RRC roll-off response (with some oscillation), partly because we used RRC filter as the initial taps for the CMA-ES optimizer. A significant ripple is also seen for RMP filter. It is mainly because the ideal RMP transfer function has discontinuity and thus even longer taps are required to suppress the truncation effect.

3. Nonlinear transmission performance

Fig. 4 shows the simulated nonlinear transmission performance for 15, 30, and 60 spans of dispersion unmanaged SSMF links. We can see that our optimized FIR filter achieves 0.14–0.23 dB improvement at peak Q factor in comparison to the conventional RRC filter. Although the optimized filter has a small degradation in the linear regimes, a more significant gain up to 0.62 dB can be obtained in the highly nonlinear regimes. Note that the RMP filter does not perform better than our designed FIR filter, especially for shorter fiber distance.

4. Conclusions

We designed a pulse-shaping FIR filter via CMA-ES meta-heuristic optimizer to minimize NLI. It was verified that the optimized filter improves nonlinear performance by up to 0.23 dB compared to the conventional RRC filter without complexity increase, unlike 4-dimensional FIR [9]. We also showed the advantage over state-of-the-art RMP filter.

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