Low Complexity Multichannel Nonlinear Predistortion for Passive Optical Networks

Domaniç Lavery, Milen Paskov, Robert Maher, Benn C. Thomsen, Seb J. Savory and Polina Bayvel
Optical Networks Group, University College London (UCL), Torrington Place, London, WC1E 7JE, UK
d.lavery@ee.ucl.ac.uk

Abstract: Multichannel, digital predistortion for nonlinearity in a single span (80 km) optical transmission system is investigated. The technique is verified in experiment and simulation for $3 \times 3.125$ GBd QPSK subchannels, realising a 4 dB power budget increase.

OCIS codes: (060.4510) Optical Communications; (060.1660) Coherent Communications.

1. Introduction

The achievable reach and split ratio of a passive optical network (PON) are determined by power budget, which is inherently limited by receiver sensitivity. When the receiver sensitivity has been optimized, for example by using coherent optical network units (ONU), the power budget of a PON can only be increased by increasing the launch power of the signal, if the network is to remain passive. However, high capacity PONs have been shown to be limited in this regard by signal distortions induced by fiber nonlinearity [1]. This leads to a trade off between maximizing received power and minimizing the induced fiber nonlinearity.

A further issue arises when using wavelength division multiplexed (WDM) channels on a tight frequency grid (i.e., an ultra-dense (UD) WDM configuration). Fiber nonlinearity will have an impact on these channels due to self phase modulation (SPM) but, additionally, due to cross phase modulation (XPM). SPM could be compensated at the ONU using digital back propagation (DBP) [2], however the sensitivity gain is limited by the noise introduced in the receiver (i.e., shot noise) [3], and the tolerable ONU complexity. To overcome this issue, DBP could be applied as a signal predistortion at the optical line terminal (OLT), exploiting the high transmitted signal-to-noise ratio (SNR)\(^1\), while moving complexity away from the ONU. DBP is known to be computationally expensive, even for core network applications, although it is possible to reduce the complexity by limiting the number of dispersion compensation stages. Over the relatively short distances considered for a PON, the nonlinearity can be assumed to act independently of the dispersion, reducing the complexity to a single step nonlinearity compensation. To this end, the much simpler SPM predistortion technique – a nonlinear phase shift – has been extensively investigated, albeit for multispan links [4, 5].

In light of recent developments in the sample rate and resolution of digital-to-analog converters (DAC), the use of both Nyquist pulse shaping [6,7] and subchannel generation have been proposed for PONs [8]. If advanced modulation formats are employed (rather than, for example, on-off-keying), then the bandwidth efficiency of these formats can be exploited, allowing the generation of a greater number of subchannels from a single DAC, while maintaining the data rate per channel. Furthermore, Nyquist pulse shaping allows a much narrower channel spacing, further increasing the bandwidth efficiency and, hence, the number of possible subchannels\(^2\). The wide electrical bandwidth of the DAC in the OLT can be exploited to extend the nonlinear predistortion technique to compensate both SPM and XPM.

While previous work has generally considered nonlinear predistortion for multi-span (repeated) systems, the single span is a special case in that, to a first approximation, the induced nonlinearity can be assumed to operate on the signal independently of additive noise and chromatic dispersion. In this paper, we present a proof of concept implementation of a low complexity, multichannel, nonlinear predistortion technique, based on a simple nonlinear phase shift at the OLT, using a coherent long-reach (80 km) PON as a testbed.

2. Nonlinear Predistortion

The nonlinear predistortion technique considered is a multi-channel nonlinear phase shift applied on a sample-by-sample basis, and implemented as in Eq. (1) where $E_{x,y}(k)$ are the $k^{th}$ samples of the transmitted signal on the $X$

\(^1\)For a high transmitted SNR, transmitter-side DBP will effectively linearize the transmission channel in a single span transmission system.

\(^2\)Nyquist pulse shaping of channels has the additional benefit of crosstalk mitigation at the ONU [6, 7], and would likely be used regardless of the method of channel generation.
and Y polarizations, respectively, and $\gamma_{\text{eff}}$ is the effective nonlinear coefficient, which is proportional to the product of the fiber nonlinear parameter, the total launch power, and the nonlinear effective length. The assumption for this predistortion is that the nonlinearity acts independently of chromatic dispersion.

$$E_x(k) \leftarrow E_x(k) e^{i\gamma_{\text{eff}}(|E_x(k)|^2 + \frac{1}{3}|E_y(k)|^2)}$$
$$E_y(k) \leftarrow E_y(k) e^{i\gamma_{\text{eff}}(\frac{2}{3}|E_x(k)|^2 + |E_y(k)|^2)}$$

(1)

For m-ary quadrature amplitude modulation (QAM), this can be implemented using a $\log_2(m)$ bit lookup table (LUT) or, for dual polarization (DP) m-ary QAM, two $2\log_2(m)$ bit LUTs. If digital subchannel generation or pulse shaping are applied to the signal (as they are here), then the computational complexity will depend on the number of quantization levels used to represent the continuous waveform. In this case, it may be more efficient to compute the multiplications directly, noting that this process can be simplified by exploiting the repeated operations. Crucially, the filtering process is memoryless and will therefore be significantly less computationally expensive than DBP, making it suitable for an access network application.

3. Simulation and Experimental Verification

In the following, only single polarization transmission was considered due to limited DAC resources (four independent DACs are required to generate a dual polarization predistorted signal, as polarization multiplexing using a delay line stage cannot be used to emulate the predistorted signal). However, the analysis presented herein is valid for dual polarization transmission as the nonlinear phase shift applied can computed for the dual polarization scenario, Eq. (1).

The nonlinear predistortion technique was simulated and verified experimentally. In simulation, three subchannels were generated and detected ideally, with each modulated at 3.125 Gbd with $2^{17}$ randomly generated QPSK symbols. Root raised cosine (RRC) filtering was applied to these subchannels with a roll-off factor, $\alpha = 0.001$, allowing the subchannels to be spaced with a 100 MHz guard interval without linear interchannel interference. Where nonlinear predistortion was considered, it was applied at this point.

Transmission over 80 km of standard single mode fiber (SSMF) was simulated using the split step Fourier method with a 100 m step size. The received signal power was set, and the signal was detected using an ideal coherent receiver (shot noise, only), followed by linear compensation of the fiber dispersion and a matched RRC filter.

In the experimental investigation (Fig. 1) the subchannel generation, RRC pulse shaping and nonlinear predistortion were computed ideally offline. A DAC, operating at 25 GSa/s (6 bit hardware resolution, 14 GHz 3 dB bandwidth), was used to drive a nested Mach-Zehnder modulator (‘IQ mod.’), modulating the subchannels onto the output of an external cavity laser (ECL) at a wavelength of 1550 nm (100 kHz linewidth).

The launch power of this signal was set using an erbium doped fiber amplifier (EDFA) followed by a variable optical attenuator (VOA), before being passed through 80 km of SSMF. The received power was set using a second VOA before entering a phase- and polarization-diverse coherent receiver. Intradyne detection was achieved using a second ECL (linewidth 100 kHz) as the local oscillator (LO) laser. The signal was digitized at 50 GSa/s using a digital sampling oscilloscope, before resampling to 2 Sa/symbol. The receiver DSP comprised ideal matched filtering, followed by a 5-tap adaptive equalizer (constant modulus algorithm) and 4th power carrier recovery [9].

4. Results

Fig. 2(a) shows the experimentally measured receiver sensitivity, evaluated in the back-to-back configuration and for a launch power of 5.2 dBm/subchannel. In this scenario, there is a 1 dB sensitivity penalty at a bit error rate (BER) of...
$10^{-2}$ for moving to the nonlinear regime, without predistortion. When nonlinear predistortion is applied, this penalty is reduced to 0.1 dB. Note that this also removes the error floor induced by nonlinear interference.

Fig. 2(b) shows the impact that this technique has on power budget (here defined as the difference in launch power and received power at a $10^{-2}$ BER). It is found that the power budget can be increased by 4 dB when nonlinear predistortion is applied, in good agreement with simulations. In the case of a PON incorporating a passive power splitter, this would permit an extra 3 dB split, potentially doubling the number of ONUs served.

5. Conclusions

A low complexity, digital, multichannel, nonlinear predistortion technique was presented for use in access networks. The performance was investigated by numerical simulation for transmission of $3 \times 3.125$ GBd QPSK subchannels over 80 km SSMF and validated experimentally. The improvement in power budget was found to be 4 dB; potentially enabling a doubling of split ratio in a power-splitting PON. Perhaps more significantly, this technique could be used to recover the sensitivity sacrificed in using higher order modulation formats in self-coherent optical access networks [7]. Herein, the efficacy of nonlinear predistortion was evaluated for a coherent access network, however the technique is independent of the chosen receiver, and would be equally applicable to a WDM-PON using direct detection receivers.

Acknowledgement

The authors acknowledge EPSRC UNLOC (EP/J017582/1) and EPSRC COSINE (EP/I012702/1) projects, and The Royal Academy of Engineering / The Leverhulme Trust for financial support. The authors wish to the Dr. Lidia Galdino for comments on earlier drafts of this paper.

References