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REVIEW ARTICLE

Performance of coherent optical fiber transmission systems

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Abstract A brief overview of recent experimental research on coherent optical fiber transmission systems at Queen's University is presented. Exemplary results are described that exploit real-time signal processing to assess the impact of cascaded optical filtering.

Keywords coherent optical fiber transmission, cascaded optical filtering

1 Introduction

Modern optical fiber transmission systems utilize advances in digital signal processing (DSP) and digital-to-analog converters (DACs) in the transmitter, and analog-to-digital converters (ADCs) and DSP in the receiver [1]. Modulated optical signals are generated with precise control of the amplitude and phase, thus allowing for significant increases in the amount of digital data transmitted by each channel. Moreover, each channel consists of two orthogonally polarized signals with the same carrier frequency, thereby doubling the per-channel bit rate. In the receiver, the combination of coherent detection, ADCs and DSP allows for implementing functions necessary to recover the transmitted information (e.g., resolving the two dual-polarization (DP) signals and compensating for transmission impairments).

In commercial systems, the DSP and DACs/ADCs are realized as complex and expensive application specific integrated circuits (ASICs). ASIC functionality is frequently emulated by using a computer for off-line signal processing and an arbitrary waveform generator to act as the DACs by converting stored sample values for the digital signals to analog electrical drive signals that are applied to a DP in-phase/quadrature optical modulator. The received signal is detected using a coherent receiver, four-channel real-time sampling oscilloscope to perform the analog-to-digital conversion, and off-line signal processing. This approach has the advantage of supporting exploratory and applied research on DSP algorithms for the transmitter and/or receiver. The real-time signal processing of an ASIC can be used to assess the impact of transmission impairments on system performance by taking advantage of the rapid acquisition of results.

Recent research conducted at Queen's University has addressed topics related to transmission impairments and performance characterization. These topics include the following.

An efficient procedure has been presented for evaluating the performance of multidimensional modulation formats in terms of the achievable information rate. It allows the explicit properties of signal constellations to be captured and is applicable to fully loaded dense wavelength division multiplexed transmission systems. The efficiency of the procedure facilitated formulating multidimensional quadrature-amplitude-modulation (QAM) constellation subset selection as a combinatorial optimization problem [2]. The approach allows obtaining a polarization balanced (PB) version of polarization-switched quaternary phase shift keying (PS-QPSK). PB-PS-QPSK is an eight-dimensional (8D) polarization balanced format; the signal vector extends over two consecutive time slots and satisfies

$$A_{m,x}A^*_{m,y} + A_{m+1,x}A^*_{m+1,y} = 0,$$

where $A_{m,x}$ and $A_{m,y}$ are the symbol sequences for the X- and Y-polarization signals. For dispersion managed links, polarization crosstalk can be mitigated if the constellation exhibits this temporal correlation. The PB-PS-QPSK format has the same constellation entropy (6 bits/8D symbol) and power efficiency as the PS-QPSK format. The advantage for the PB-PS-QPSK format over the PS-QPSK format is shown in Fig. 1 for 41 channel nonlinear transmission over a 10000 km dispersion managed link at 35 Gbaud. The dependence of the achievable information rate (AIR) on the per-channel launch power indicates increases of 0.09 bits/8D symbol at optimum power and 0.25 bits/8D symbol at -3 dBm for the PB-PS-QPSK

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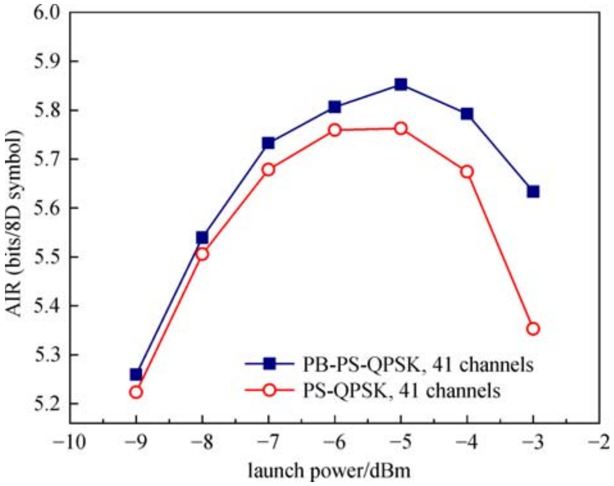

Fig. 1 Dependence of estimated 8D AIR on launch power for PB-PS-QPSK and PS-QPSK for 41 channel nonlinear transmission over a 10000 km dispersion managed link at 35 Gbaud. © 2018 IEEE. Reprinted, with permission, from IEEE/OSA Journal of Lightwave Technology

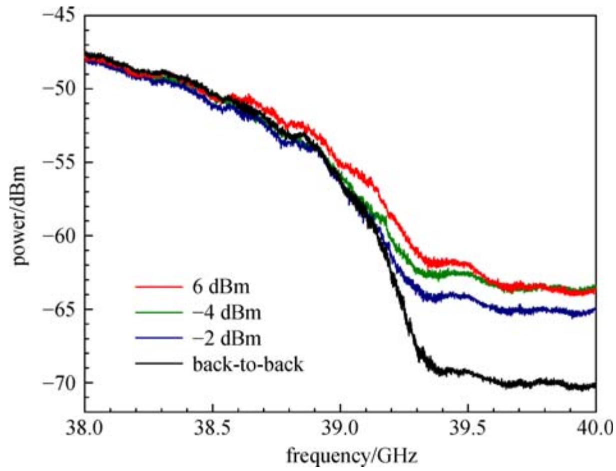

Fig. 3 Normalized measured spectra for a 224 Gb/s DP 16-QAM signal, X-polarization component. Resolution bandwidth of 300 kHz, video bandwidth of 300 kHz. © 2016 IEEE. Reprinted, with permission, from IEEE Photonics Technology Letters

format compared to the PS-QPSK format.

A comparative assessment of a nonlinear pre-distorter (NLPD) at the transmitter, and a maximum-a-posteriori (MAP) probability detector, time-domain Volterra nonlinear equalizer (VNLE), or sparse-VNLE at the receiver has been presented for compensating pattern-dependent distortion that can occur in high symbol rate transmitters and receivers. Experimental results were obtained for a 1 Tb/s DP 16-QAM superchannel signal with three subcarriers [3]. For transmission over 1500 km of single-mode fiber, the dependence of the bit error ratio (BER) on launch power is shown in Fig. 2 for the four compensation techniques. The launch power ranges for a BER below the forward error correction coding threshold BER of 1.9×10^{-2} are 2.1, 2.3, 2.8 and 3.2 dB for the sparse-VNLE, VNLE, MAP detector, and NLPD, respectively.

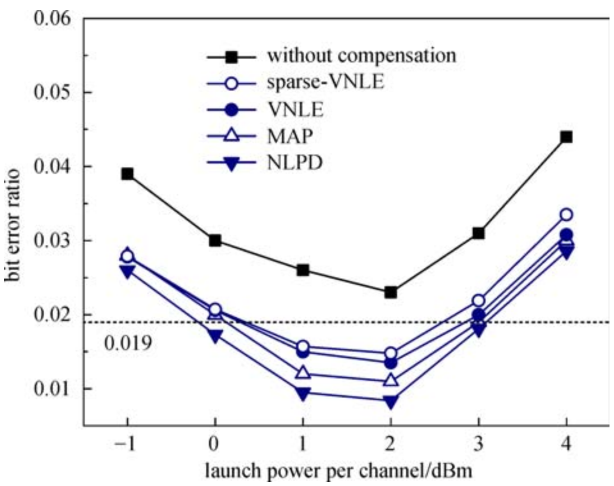

Fig. 2 Dependence of the BER on launch power for a 1.206 Tb/s superchannel signal and transmission over 1500 km of single-mode fiber with a NLPD, MAP detector, VNLE and sparse-VNLE. © 2016 IEEE. Reprinted, with permission, from IEEE Photonics Technology Letters

Balanced heterodyne detection and a gated microwave spectrum analyzer have been used to precisely measure the spectral broadening due to intra-channel fiber nonlinearities. Polarization resolved spectra for a 200 Gb/s DP 16-QAM signal have been quantified in terms of the spectral edge power which serves as a useful metric for capturing the effects of both fiber nonlinearities and amplified spontaneous emission noise [4]. Figure 3 shows measurements of the high frequency edge of the signal spectra. The pulse shape for each polarization component was square-root raised-cosine with a roll-off factor of 0.05. Fiber nonlinearities cause broadening of the spectrum for a launch power of 6 dBm.

The performance implications of passband impairments and bandwidth narrowing caused by the cascading of optical filters in reconfigurable optical add-drop multiplexers (ROADMs) have been investigated using a 100 Gb/s DP QPSK transceiver. To determine the impact on system margins, a methodology based on extreme value statistics was used [5]. This last topic is described in more detail.

The impact of cascaded filtering on system performance and techniques to mitigate the filtering penalties have been assessed experimentally using both offline signal processing [6–15] and real-time signal processing [16–23]. The experiments used either a recirculating loop to repeatedly apply an optical signal to the same optical filter(s) [7–11,14,18], or straight-line cascades of distinct optical filters [6,7,16,17,19,20,23]. The performance implications of 1) passband impairments and bandwidth narrowing [21] and

2) bandwidth narrowing and center frequency offset [22] have recently been investigated by considering emulated realizations of the cascaded response and real-time signal processing. Emulation of the overall cascaded filter response allows a relatively large number of possible realizations to be considered.

2 Methodology and experiment

The overall passband responses for a cascade of ten filters were generated offline. The passband impairment for each filter is characterized by a slope about the carrier frequency with amplitude A_s, and ripple with amplitude, frequency and phase offset A_r, f_r and ϕ_r, respectively. The phase response has a negligible effect for cases of interest and is neglected [24]. Randomly selected passband impairments were applied to each of the ten filters in a cascade. A_s was uniformly distributed on the interval $[-R_s, R_s]$ with R_s = 0.25 dB/50-GHz and A_r was uniformly distributed on the interval $[0.005, R_r]$ with $R_r = 0.02$. f_r was set to 50.3 GHz and ϕ_r was uniformly distributed on the interval $[0, 2\pi]$. The overall passband response for the cascaded filters was numerically generated for 1000 sets of ten filter responses. The overall response of the filter cascade is also specified by the bandwidth BW and offset of the center frequency f_o relative to the carrier frequency. The overall responses were realized using a programmable optical filter (POF) with a resolution of 1 GHz and a variable bandwidth optical filter (VBOF). The POF was used to set the passband impairment and the VBOF was used to set the 3-dB bandwidth BW and center frequency. Here, f_o was set to 0.

The experimental setup is shown in Fig. 4. With overhead for forward error correction (FEC) coding and framing, the transmitted 137.84 Gb/s DP QPSK signal used a root raised cosine pulse shape with a roll-off factor of 0.14 and was generated by a Ciena WaveLogic 3 transceiver. The modulation rate was 34.46 Gbaud. For this transceiver, the threshold for the pre-FEC bit error ratio (BER) is 0.034. Each passband response for a cascade was uploaded to the POF. The combined frequency response was then measured using an optical vector analyzer. The DP QPSK signal was applied to the two filters and then noise-loaded to set the optical signal-to-noise ratio (OSNR) at the receiver. The noise-loaded signal was filtered to reject out-of-band noise using an optical filter with a bandwidth that exceeded the signal bandwidth in order to avoid any further distortion of the signal. Real-time digital signal processing was performed by the transceiver and estimates of the pre-FEC BER were obtained based on the FEC decoding.

The values for the pre-FEC BER were converted to signal-to-noise ratios (SNRs) E_s/N_0 using [25]

$$\frac{E_s}{N_0} = 2[\mathrm{erfc}^{-1}(4(1-\sqrt{1-\mathrm{BER}}))]^2,$$

where erfc is the complementary error function. Given the statistical variation of the SNR, the probability that it is less than a specified value SNR_0, which corresponds to a BER value BER_0 at or below the FEC threshold, is of interest. One approach to estimate the probability $\mathrm{Prob}(\mathrm{SNR} < \mathrm{SNR}_0)$ is to fit a probability density function to measured results. However, given that SNR_0 values of interest are in the lower tail of the density function, it is difficult to obtain reliable results as differences in the fitting procedure can lead to significant variations in the estimated probabilities. Extreme value statistics can be used to circumvent this issue by considering n values of the SNR for different cascaded filter responses as a sequence of independent identically distributed random variables. The probability distribution function $F_n(x)$ for the minimum of this sequence, $\mathrm{SNR}_{\min,n} = \min\{\mathrm{SNR}_1, \mathrm{SNR}_2,\ldots, \mathrm{SNR}_n\}$, is sought. The statistical methods of extreme values provide the important result that there are limiting forms of $F_n(x)$ as $n \to \infty$ regardless of the actual distribution for the random variable SNR [26]. The Gumbel probability distribution function is used here.

3 Results

Figure 5 illustrates an example of the measured frequency response for an emulated response with a bandwidth BW of 38 GHz. The inset in Fig. 5 shows the spectrum of the DP QPSK signal obtained using a spectrometer with a resolution of 15 MHz. The signal has a spectral occupancy of 39.6 GHz.

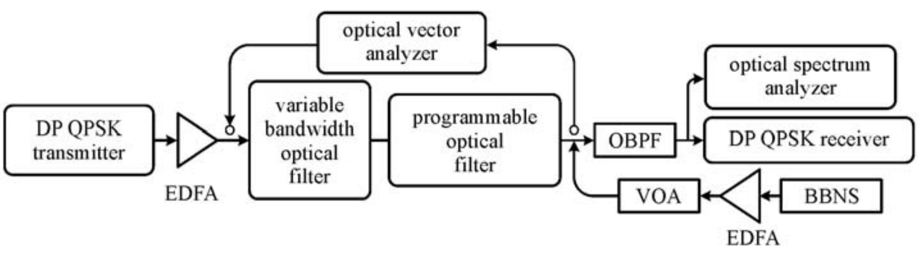

Fig. 4 Experimental setup. EDFA: erbium doped fiber amplifier; OBPF: optical bandpass filter; VOA: variable optical attenuator; BBNS: broadband noise source. © 2017 IEEE. Reprinted, with permission, from IEEE/OSA Journal of Lightwave Technology

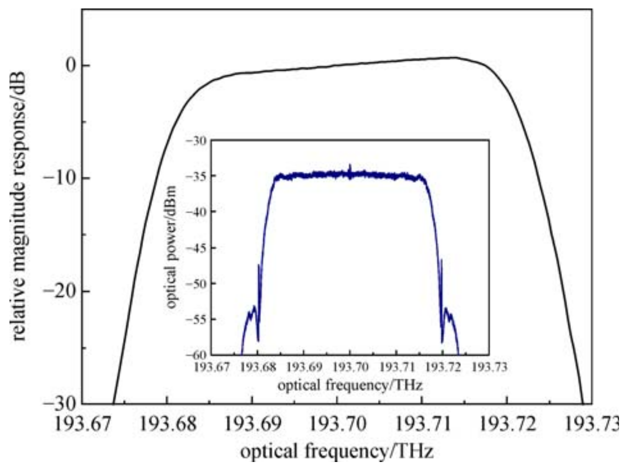

Fig. 5 Measured response for one of the 1000 cascaded filter responses, BW = 38 GHz. Inset shows the spectrum of the 35 Gbaud DP-QPSK signal. © 2017 IEEE. Reprinted, with permission, from IEEE/OSA Journal of Lightwave Technology

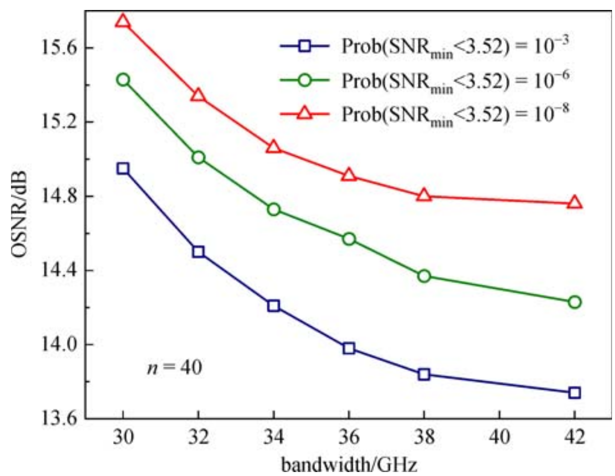

Fig. 7 Dependence of the required OSNR on the overall bandwidth of the filter cascade for three values of Prob(SNR$_{min}$ < 3.52). © 2017 IEEE. Reprinted, with permission, from IEEE/OSA Journal of Lightwave Technology

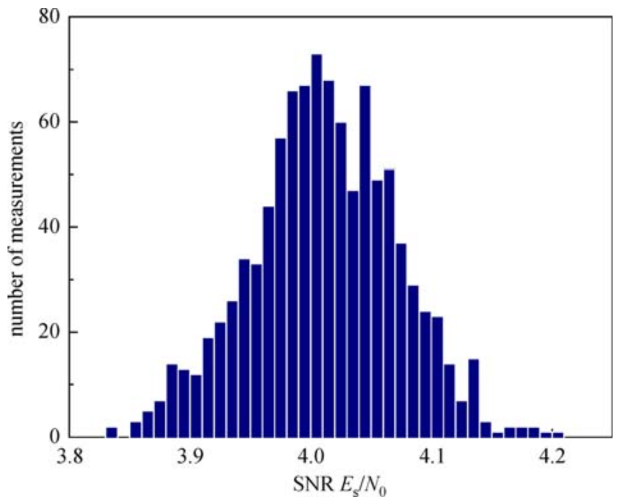

Fig. 6 Histogram of the SNR E_s/N_0 for 1000 realizations of the cascaded filters for OSNR = 13.8 dB. © 2017 IEEE. Reprinted, with permission, from IEEE/OSA Journal of Lightwave Technology

A histogram of the values of the SNR for the results of one measurement for 1000 overall responses is shown in Fig. 6 for BW = 36 GHz and OSNR = 13.8 dB. The mean value of the SNR is 4.01 and the standard deviation is 6.09×10^{-2}.

From results such as these, the required OSNRs for specified values of Prob(SNR$_{min}$ < 3.52) can be extracted as shown in Fig. 7 for n = 40 as a function of the bandwidth BW. The value of SNR$_0$ = 3.52 corresponds to BER = 0.03. The three values of Prob(SNR$_{min}$ < 3.52) represent different levels of tolerating the pre-FEC BER exceeding the FEC threshold. In practical applications, this tolerance could range from cases where an adversely affected channel can be re-provisioned to where its occurrence is to be very infrequent. This approach for assessing the implications on system performance allows anticipated variations in the cascaded frequency response to be quantified in terms of the pre-FEC BER exceeding the FEC threshold.

4 Conclusion

By emulating the overall responses for 1000 cascades of ten filters using the combination of a programmable optical filter and variable bandwidth optical filter, the impact of the statistical variations in the responses was assessed using SNR values obtained from corresponding estimates of the pre-FEC BER. The results were interpreted using extreme value statistics to consider the probability that the minimum of n observations of the SNR is less than a specified value.

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