1.15 Tb/s Nyquist PDM 16-QAM Transmission with Joint Matched Filtering and Frequency-Domain Equalization

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Abstract: We experimentally demonstrate 18×64-Gb/s Nyquist PDM-16QAM signal transmission over 800-km single-mode fiber. The receiver matched filtering and channel's linear impairment compensation are jointly processed with a single linear filter, greatly reducing the computational complexity.

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1. Introduction

Single-carrier systems with transmitter digital Nyquist filtering have been demonstrated as promising schemes to support symbol rates approaching the channel spacing of wavelength-division-multiplexing (WDM) systems [1-3]. Such *Nyquist-WDM* relaxes the receiver hardware requirements compared with optical orthogonal frequency division multiplexing (OFDM) [4], because the channels do not overlap.

For Nyquist-WDM systems to achieve an overall raised-cosine (RC) pulse shape, to satisfy the Nyquist theorem, root-raised-cosine (RRC) filters are typically implemented in both transmitter and receiver side for pulse shaping and matched filtering, respectively. Finite impulse response (FIR) filters with many taps are typically required to implement RRC filters with small roll-off factors, which incur a high computational cost [5]. For most of the previous Nyquist-WDM demonstrations [1, 2], static chromatic dispersion (CD) equalizers and blind adaptive equalization are applied for linear channel impairment compensation, while an independent receiver-side RRC matched filter is necessary before the adaptive equalizers to achieve optimal performance.

Training-aided frequency domain equalization (TA-FDE) is a reliable technique for linear impairment compensation [6-8]. In particular, the single-stage TA-FDE (SS-TA-FDE) allows compensation of all of the linear impairments with a single multiple-input multiple-output (MIMO) equalizer [7, 8], which is computationally efficient and modulation-format transparent. The RRC filter can be processed in the frequency domain [9], and so can be combined with a fractionally spaced frequency-domain channel equalizer, to reduce the computational effort.

Training-based MIMO channel estimation in a Nyquist-WDM system has only been demonstrated once [3]. However, the MIMO equalizer was independent of the matched filtering and CD equalizer. In this paper we combine Nyquist-WDM transmission with Nyquist SS-TA-FDE (N-SS-TA-FDE), where a Nyquist-windowing process is applied to the coefficients of SS-TA-FDE instead of using a separate RRC matched filter. The proposed concept is experimentally demonstrated with a 18×64-Gb/s Nyquist polarization-division-multiplexing (PDM) 16-QAM system with 800-km transmission, the modified frequency domain equalizer combines the matched filtering and linear equalization in a single step, achieves comparable performance to when the matched filter is implemented separately. The combined method is a significantly more computationally-efficient receiver DSP solution for Nyquist WDM systems.

2. Transmitter and Receiver DSP

Figure 1a shows the transmitter side digital signal processing (DSP) used for Nyquist PDM-16QAM with TA-FDE. The data bits are first mapped into 16-QAM symbols, and then the training sequences (TS) are inserted periodically before every 10000 information symbols for channel estimation. Overlap and save processing is adopted for FDE processing, therefore no cyclic prefix is needed. The signals are then up-sampled to 2 samples/symbol, and followed by near ideal Nyquist-pulse-shaping RRC filter with a 0.01 roll off factor. A pre-emphasis filter is then used to overcome the frequency roll-off of the digital to analog converter (DAC). In a real system, the pre-emphasis and Nyquist filter can be combined and implemented in frequency domain to reduce computational complexity. In order to generate a higher baud rate signal with a limited DAC sample rate, the signals are finally resampled to 1.25 samples/symbol before uploading to the DAC.

Figure 1(b) shows the offline DSP algorithms. After front-end impairment correction, the received signals are resampled to 2 samples/symbol. For normal SS-TA-FDE, RRC matched filtering is conducted to meet the Nyquist criterion. After frequency offset compensation and frame synchronization, the TS are extracted for channel estimation. The single-stage MIMO FDE taps, **E**, are setup for linear channel impairment compensation, with the equalizer output fed into the decision-directed maximum likelihood phase recovery circuit, before bit error rate (BER) counting. Compared with the single-channel SS-TA-FDE demonstration [7, 8], the only additional DSP block for SS-TA-FDE in Nyquist-WDM system is the receiver side matched filter. For the proposed N-SS-TA-FDE, the matched filtering process is eliminated. Instead, there is an extra frequency-domain windowing process for the equalizer taps setup. That is, after the original frequency-domain MIMO filter taps **E** are determined, each sub-vector of the 2×2 matrix (e.g. $\mathbf{E}_{xx}$) passes through a rectangular window (Nyquist windowing) to set the equalizer coefficients outside the Nyquist frequency range to be zero. This operation combines all linear filters in a single MIMO filter, avoiding a long-tap (256-taps in this work) RRC filter for each polarization, leading to a computationally-efficient DSP solution for our Nyquist-WDM system.

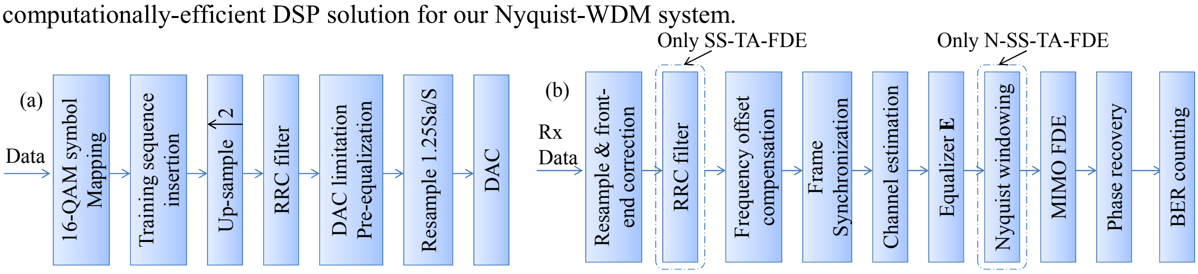

Fig. 1. Conceptual block diagram for: (a) transmitter side and (b) receiver side DSP design for N-SS-TA-FDE system.

3. Nyquist PDM-16QAM experiment demonstration and discussion

The experimental setup is shown in Fig. (2). The output of the transmitter external cavity laser was modulated by an intensity modulator (IM), which was over driven to generate a 9 comb lines with 16.1 GHz spacing, followed by a Finisar Waveshaper (WS) for power equalization of the comb lines. A 10-Gsamples/s arbitrary wave generator (AWG) was employed to generate 8-GBaud baseband signals (with 1.25 samples/symbol digital input), a low-pass filter (LPF) was then used to eliminate the spurious frequency components. The RF signals were amplified and used to drive an Sumitomo I/Q modulator, producing a half-filled spectrum (inset (*i*) of Fig. (2)). The signals were then split into two paths with a 50:50 coupler. One path was frequency shifted by 8.05-GHz using another I/Q modulator, passed through an optical delay line to de-correlate the channels at the shifted spectrum from the channels at the original half spectrum. After amplification, the shifted spectrum was combined with the original path through another coupler. A Kylia polarization division multiplexing (PDM) emulator was then used to form an 18-band PDM signal. The 144.9-GHz full-filled spectrum is shown as the inset (*ii*) of Fig. (2), and there is only a 50-MHz guard band between the adjacent channels. The PDM signals were then transmitted through an 800-km EDFA-amplified fiber link. The signal spectrum after transmission is shown as inset (*iii*) of Fig. (2). An ASE source (attenuator and EDFA) was used to control the OSNR sensitivity in the back-to-back (B2B) scenario. A 10% tap was taken from the signal to measure the OSNR using an optical spectrum analyzer (OSA). The remaining 90% of the signal was then first filtered by another Waveshaper to suppress out-of-band noise and fed into an integrated U^2T coherent receiver. Finally the RF signals were captured by a 4-channel 40-GSa/s Agilent digital oscilloscope for offline processing.

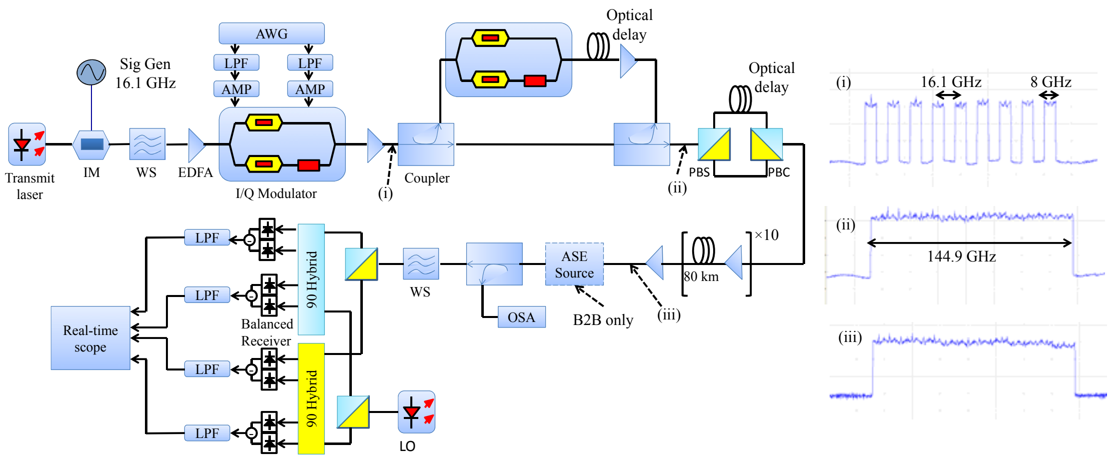

Fig. 2. Experimental setup for 1.15 Tb/s Nyquist PDM-16QAM system.

Alamouti-coding Golay sequences were used as the TS for SS-TA-FDE processing [8]. 156-symbol TS (matching exactly the delay between two polarizations) were sent for each polarization, comprising of two 64-symbol sub-TSs, each with a 28-symbol guard interval. The equalizer operated at two-times oversampling using a 128-point FFT/IFFT. After accounting for 7% FEC overhead, the system net data rate is 1.06-Tb/s and the spectral efficiency is 7.31bits/s/Hz. For N-SS-TA-FDE, the 63 highest-frequency points of each sub-vector of the 2×2 MIMO FDE were set to 0 for Nyquist-windowing, which is equivalent to nulling almost half of the input signal frequencies.

The measured Q^2-factor ($Q^2(dB) = 20\log_{10}(\sqrt{2}erfc^{-1}(2BER))$) of the 9th channel in B2B transmission for different received OSNR values (0.1-nm reference bandwidth) is depicted in Fig. 3(a), where four different equalization schemes are compared: (*i*) the SS-TA-FDE with RRC filter; (*ii*) the N-SS-TA-FDE scheme; (*iii*) conventional CD equalization with blind MIMO equalization after RRC-filtering [10]; and (*iv*) SS-TA-FDE without RRC filter. Without the receiver Nyquist matched filter, SS-TA-FDE has the worst performance: there is ~2-dB Q^2 penalty compared to the other receiver DSP schemes. All the other three equalization methods achieve similar performance. The equalized constellation diagrams with 31.9-dB OSNR with N-SS-TA-FDE method are shown as an inset in Fig. 3(a). Within the three cases that can achieve similar performance, the blind equalizer method implement the Nyquist matched filter, CD equalizer and MIMO polarization de-multiplexing all separately. Assuming the receiver RRC filter and CD equalization are implemented with 256-tap/128-tap FFT/IFFT 50% overlap FDE, respectively, and with 16-tap frequency domain MIMO blind equalizer [10], the blind solution (*iii*) requires about 126 complex multiplications per symbol (cm/symbol). For the normal SS-TA-FDE (*i*) with RRC filter and 128-tap single-stage MIMO equalizer, the computational cost would be about 62 cm/symbol. While the N-SS-TA-FDE combines all three filters into a single MIMO processing, only costs 26 cm/symbol, leading to most computationally-efficient solution for our Nyquist-WDM system.

Figure 3(b) shows the performance versus launch power for the 13th channel with N-SS-TA-FDE after 800-km transmission, it can be found that the optimal performance for the system occurs at 4-dBm launch power. The measured results for all 18 bands at 4-dBm launch power after 800-km are shown in Fig. 3(c), where N-SS-TA-FDE achieves similar results as the SS-TA-FDE with RRC filter, demonstrating the feasibility of combining the receiver Nyquist matched filtering within the fractionally spaced SS-FDE. All the bands are measured to be above the 7% FEC limit, with representative equalized signal constellations shown as inset in Fig. 3(c). Actually, the performance of most channels using N-SS-TA-FDE is slightly poorer than their counterparts (by about 0.2-dB), this may be due to the receiver DSP block size being only half of the transmitter Nyquist filter size, which means the MIMO equalizer has a lower spectral resolution than the independent RRC filter.

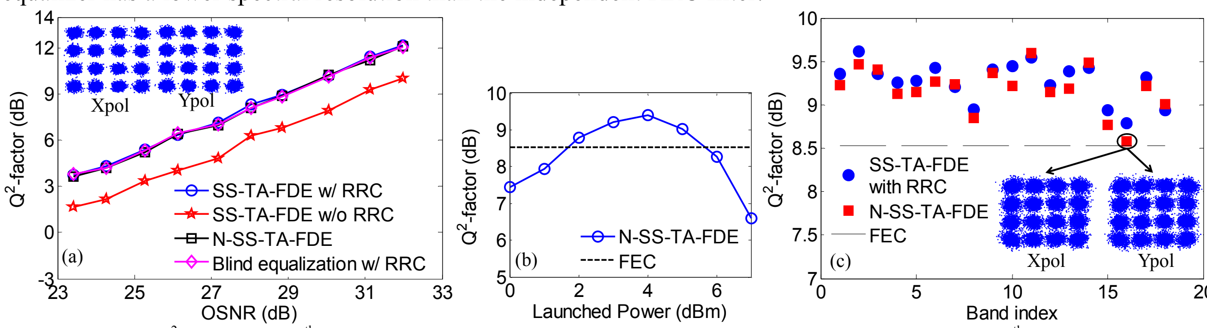

Fig. 3. Measured Q^2-factor of: (a) 9th band versus OSNR in B2B transmission with different equalization schemes, (b) 13th band versus launched power after 800-km transmission with N-SS-TA-FDE, and (c) all bands after 800-km using SS-TA-FDE with RRC or N-SS-TA-FDE.

4. Conclusion

We report a 1.15-Tb/s Nyquist PDM 16-QAM transmission over 800-km SSMF. The receiver Nyquist matched filtering and channel linear impairment compensation can be jointly processed with a single MIMO equalizer by nulling the equalizer taps at the frequency points beyond the Nyquist frequency, thereby avoiding a separate Nyquist receiver matched filter. This greatly reduces the computational complexity with negligible performance degradation. After 800 km, all sub-channels were still below the hard FEC limit.

5. References

[1] J. –X. Xia, *et al.*, ECOC'2010, paper PDPB10.
[2] X. Zhou, *et al.*, JLT, **30**, 553-559 (2012).
[3] Z. Zheng, *et al.*, Opt. Express, **21**, 17505-17511 (2013).
[4] G. Bosco, *et al.*, PTL, **22**, 1129-1131 (2010).
[5] X. Zhou, *et al.*, JLT, **27**, 3641-3653 (2009).
[6] B. Spinnler, *et al.*, OFC'2013, OM4B.3.
[7] A. V. Tran, *et al.*, PTL, **24**, 885-887 (2012).
[8] C. Zhu, *et al.*, OFC'2013, paper OW4B.5.
[9] J. Wang, *et al.*, JLT, **30**, 3679-3686 (2012).
[10] C. Zhu, *et al.*, IEEE Photon. J., **4**, 1653-1661 (2012).