Computationally-Efficient DSP-based MIMO Equalization for OSNR gains in 40Gb/s OFDMA-PON

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Abstract: We present and experimentally verify a novel computationally-efficient MIMO equalization method in 40Gb/s OFDMA-PON with polarization multiplexing and direct detection. A 2.1dB DSP-based OSNR gain is achieved over 20km SSMF plus 1:32 optical split.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Next-generation passive optical networks (PON), with 40$^+$Gb/s target data rates, aggressive power budgets, and large financial incentive for maximal reuse of deployed legacy fiber, have become a highly prominent topic in optical access research and standardization activities [1-3]. A promising, cost-effective direction in this area is the upgrading the end terminals via advanced modulation and digital signal processing (DSP) [3]. This optically-transparent approach, which does not disturb the fiber network, simplifies optical components, and achieves performance gains through electronic processing is referred to as DSP-based next-generation access.

A strong example of the DSP-based approach, which currently holds the 108Gb/s/λ downstream speed record, is Orthogonal Frequency Division Multiple Access (OFDMA)-PON with polarization multiplexing (POLMUX) and direct (non-coherent) detection [4]. Through receiver-side electronic multiple input multiple output (MIMO) processing, the requirement for a coherent receiver at the optical network unit (ONU) was removed. Moreover, by using advanced POLMUX 16-QAM modulation, optical/electronic component bandwidth requirements were reduced by approximately six-fold [4]. However, while this approach greatly simplified the ONU receiver, it also increased the complexity of the required post-photodetection electronic DSP. Namely, due to direct detection, cross-polarization interference can occur in the optical receiver, which must be corrected, or equalized, in post-photodetection DSP. Unlike in POLMUX-OFDM systems with coherent detection [5], however, in this case, the inverse of a 4x4 channel estimation matrix had to be computed [4]. A single execution of this task requires an order of magnitude more operations (real multiplications) compared to 2x2 matrix inversion achieved with coherent detection. This can be prohibitive for high-speed, real-time DSP-based optical access, which must feature low processing complexity and low power consumption. Moreover, equalization based on direct channel matrix inversion, known as zero forcing (ZF), degrades performance by enhancing noise effects [5], and can thus strain the tight PON optical power budget. Computationally-efficient equalization without noise enhancement, such as maximum likelihood (ML) detection, is thus very important for practical, next-generation DSP-based optical access.

We propose a novel MIMO equalization approach for both ZF and ML detection by recognizing and exploiting a block-diagonal structure in the 4x4 channel estimation matrix. We also experimentally verify the block-diagonal ZF and ML methods on a 44.8-Gb/s (40 Gb/s after overhead) OFDMA-PON architecture, achieving significant computation savings and a 2.1dB optical signal to noise ratio (OSNR) gain over 20 km SSMF plus 1:32 optical split. By realizing key benefits via efficient electronic processing, the demonstrated result can be viewed as a highly attractive advantage of next-generation DSP-based optical access.

2. Block Diagonal MIMO Equalization

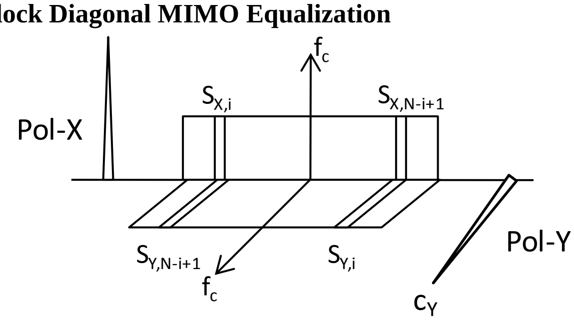


Figure 1. Frequency spectrum of POLMUX-OFDM signal.

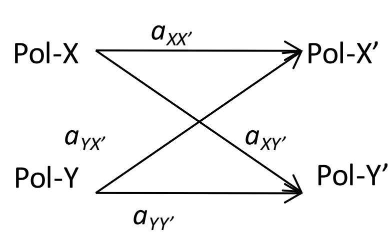


Figure 2. Channel model for POLMUX-OFDM transmission.

To describe the proposed MIMO equalization approach, the frequency domain spectrum of the POLMUX-OFDM signal is illustrated in Fig. 1, where c_X and c_Y denote frequency-orthogonal optical carriers launched in orthogonal polarizations, Pol-X and Pol-Y, respectively, f_c is the intermediate radio frequency (RF) carrier. The notation $S_{X,i}$ denotes the complex baseband OFDM symbol modulated in Pol-X onto the i^{th} OFDM subcarrier;

$S_{X,\,N-i+1}$ has an analogous meaning, where N is the Fast Fourier Transform (FFT) size. Similarly, $S_{Y,i}$ and $S_{Y,\,N-i+1}$ denote the OFDM symbols on the i^{th} and $(N-i+1)^{th}$ subcarrier in Pol-Y. Due to polarization rotation in the fiber channel, signal components on each of the two input polarization states may migrate to one of the output polarization states, Pol-X' and Pol-Y', as shown in Fig. 2. The notation $c_{XY'}$, $a_{XY'}$, for example, denotes the channel coefficients experienced by the optical carrier and OFDM symbol, respectively, that migrate from Pol-X to Pol-Y'. Gathering data from Figs. 1 and 2, the general 4x4 channel estimation matrix **H** can be formed as in (1), where **v** denotes the additive white Gaussian noise vector normalized to have identity matrix covariance .

$$\underbrace{\begin{bmatrix} c_{XX'}a_{XX'}(i) & c_{YX'}a_{YX'}(i) & c_{YX'}a_{XX'}(N-i+1) & c_{XX'}a_{YX'}(N-i+1) \\ c_{XY'}a_{XY'}(i) & c_{YY'}a_{YY'}(i) & c_{YY'}a_{XY'}(N-i+1) & c_{XY'}a_{YY'}(N-i+1) \\ c_{YX'}a_{XX'}(i) & c_{XX'}a_{YX'}(i) & c_{XX'}a_{XX'}(N-i+1) & c_{YX'}a_{YX'}(N-i+1) \\ c_{YY'}a_{XY'}(i) & c_{XY'}a_{YY'}(i) & c_{XY'}a_{XY'}(N-i+1) & c_{YY'}a_{YY'}(N-i+1) \end{bmatrix}}_{\text{Channel Estimation Matrix, } \mathbf{H}} \times \underbrace{\begin{bmatrix} S_{X,i} \\ S_{Y,i} \\ S_{X,N-i+1} \\ S_{Y,N-i+1} \end{bmatrix}}_{\text{Transmitted Symbols}} + \mathbf{v} = \underbrace{\begin{bmatrix} S_{X',i} \\ S_{Y',i} \\ S_{X',N-i+1} \\ S_{Y',N-i+1} \end{bmatrix}}_{\text{Received Symbols}} \qquad (1)$$

As shown by (1), for each received OFDM symbol, there is potential interference between 4 OFDM symbols, which can be corrected via zero forcing (ZF) by multiplying the inverse of **H**, $\mathbf{H}^{-1}$, by the received symbols. If **H** were an arbitrary matrix [4], obtaining $\mathbf{H}^{-1}$ would require on the order of 256 additional operations (real multiplications), plus 64 operations to equalize received symbols, totaling to 320 additional operations per OFDM subcarrier pair. In coherent systems, with a 2x2 matrix inverse for ZF, this total is only 44 operations.

However, the critical new observation presented here is that, due to the spectral symmetry in Fig. 1, the matrix **H** is not arbitrary, but has a unique block-diagonal structure, illustrated in Fig. 3a, where **A** and **B** are both 2x2 matrices, and the remaining values in **H** are zeros. With the block-diagonal structure, the 4x4 matrix inversion and equalization problem decomposes into two independent 2x2 problems, as shown in Fig. 3b, without incurring a performance loss. Consequently, in the new block-diagonal case, to compute $\mathbf{A}^{-1}$, $\mathbf{B}^{-1}$ and ZF equalize received symbols as in Fig. 3b, only 44 additional operations per OFDM subcarrier pair are required.

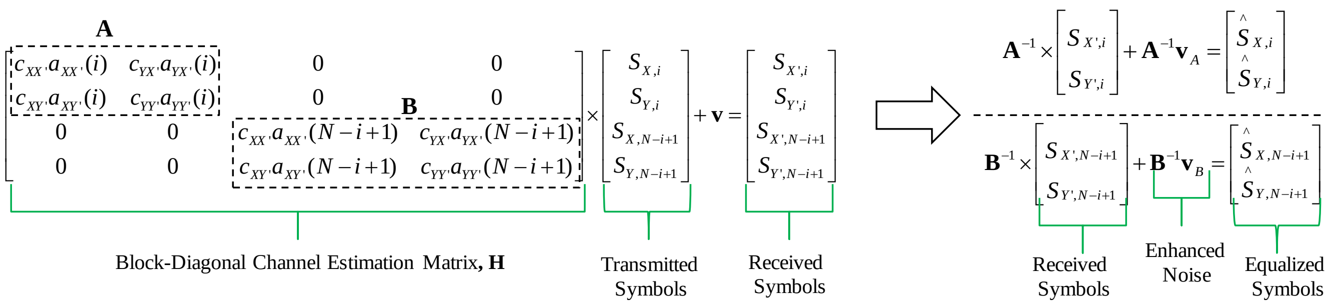


Figure 3. (a) Block-diagonal channel estimation matrix, **H** . Figure 3(b) Block-diagonal ZF equalization.

While the block diagonal ZF method of Figs. 3a-b notably reduces computationally complexity, it nonetheless results in noise enhancement, as shown in Fig. 3b, where $\mathbf{A}^{-1}\mathbf{v}_A$ and $\mathbf{B}^{-1}\,\mathbf{v}_B$ are the enhanced noise terms and $\mathbf{v}_A$ and $\mathbf{v}_B$ denote the effective noise vectors. To avoid the resulting OSNR degradation, which would impose a power budget penalty, theoretically-optimal maximum likelihood (ML) equalization can be achieved by directly applying the block-diagonal-based inputs of Fig. 3a to two parallel 2x2 ML decoders, as in (2) and (3), respectively. Due to the block diagonal structure of **H**, no additional pre-processing overhead is needed for optimal ML detection, resulting in a straightforward implementation that eliminates noise enhancement. A particularly efficient 2x2 ML decoder detailed in [6], is then sufficient for hard-decision ML equalization.

$$\mathbf{A}\begin{bmatrix} S_{X,i} \\ S_{Y,i} \end{bmatrix} + \mathbf{v}_A = \begin{bmatrix} S_{X',i} \\ S_{Y',i} \end{bmatrix} \quad (2) \qquad \mathbf{B}\begin{bmatrix} S_{X,N-i+1} \\ S_{Y,N-i+1} \end{bmatrix} + \mathbf{v}_B = \begin{bmatrix} S_{X',N-i+1} \\ S_{Y',N-i+1} \end{bmatrix} \quad (3)$$

3. Experimental Setup and Results

Fig. 5 shows the 44.8 Gb/s (40 Gb/s after overhead) experimental setup used to verify the proposed block diagonal ZF and ML algorithms over 20km of standard single mode fiber (SSMF) with a 1:32 optical split (15dB attenuation.) At the optical line terminal (OLT), the OFDM baseband signal using 16 QAM modulation was first generated offline. The FFT size was 256 and a 1/32 cyclic prefix was applied.

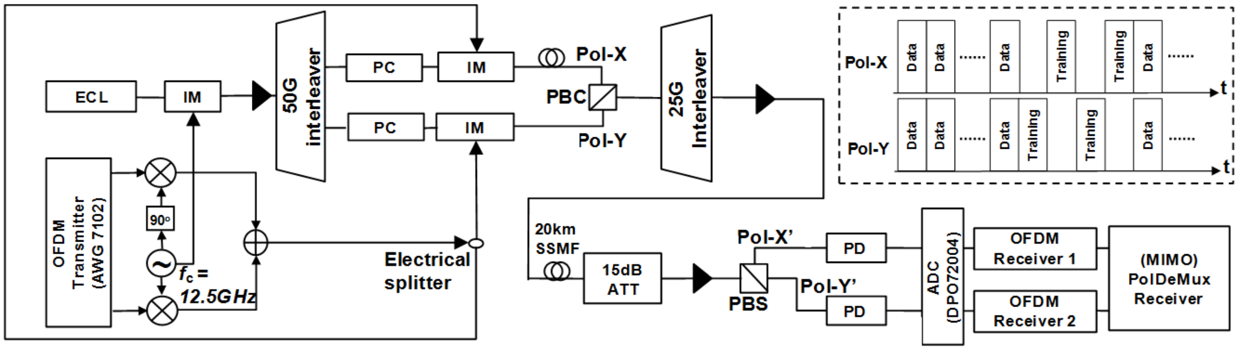
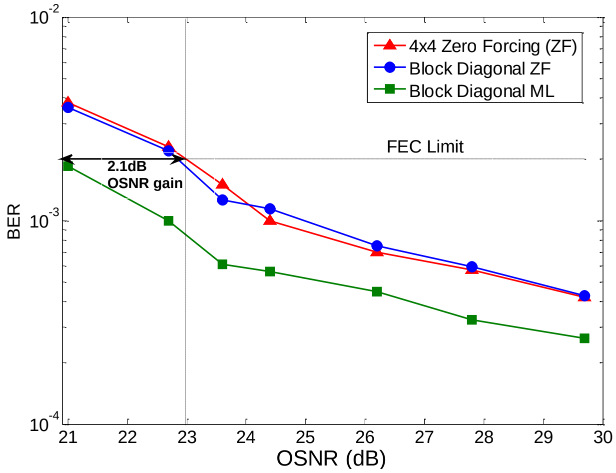


Figure 5. Experimental setup for POLMUX-OFDMA-PON with direct detection over 20km SSMF plus 15dB attenuator. (PC = polarization controller; IM = intensity modulator; ECL = external cavity laser; ATT = attenuator; PBC/PBS = polarization beam combiner/splitter)

A training sequence was added every 128 OFDM data frames. The baseband OFDM signal was uploaded into a 5GHz Tektronix arbitrary waveform generator (AWG 7102) operating at 10Gs/s with 8-bit resolution, followed by analog upconversion to f_c = 12.5GHz. To guarantee a fair comparison with previously-demonstrated results based on 4x4 ZF [7], the same optical front-end was adopted in Fig. 5, with the new block-diagonal equalization algorithms implemented in the ONU-side MIMO PolDeMux receiver. Only the electronic-domain parameters most relevant to the DSP analysis are thus presented here; for a full description, the reader is referred to [7]. The received POLMUX-OFDM signals were sampled by a 50 Gs/s Tektronix real-time oscilloscope (DPO70002), with all subsequent DSP (digital de-multiplexing, FFT, MIMO equalization) done off-line. For bit error rate (BER) computation, 0.5 million bits per polarization were evaluated and averaged across the two polarizations to obtain the final value.



DSP Algorithm	Inverse/ Filter Operations	Symbol Equalization Operations
4x4 Zero Forcing (ZF)	256	64
Block Diagonal ZF	28	16
Block Diagonal ML	107	96
ZF, Coherent OFDM	28	16

Table 1. Computational efficiency comparison for three evaluated DSP algorithms and ZF in coherent OFDM. Number of operations is calculated per one channel estimation matrix and OFDM subcarrier pair.

Figure 6 (left). OSNR versus BER comparison for MIMO equalization.

Figure 6 plots OSNR versus BER transmission performance for the proposed block diagonal ZF and ML MIMO equalization algorithms, as well as for the previously demonstrated 4x4 ZF method. As shown in Fig. 6, simplified block-diagonal ZF does not incur a performance penalty compared to computationally expensive 4x4 ZF, yet it reduces ZF complexity to the level of simple 2x2 matrix processing achieved by coherent OFDM (Table 1). Moreover, block-diagonal ML equalization achieves a 2.1 dB OSNR gain at the FEC limit (BER = $2x10^{-3}$), demonstrating both a power budget benefit and an efficient implementation (Table 1) for DSP-based PON.

4. Conclusions

We presented and experimentally verified a novel DSP-based MIMO equalization approach for OFDMA-PON with polarization multiplexing and direct detection, based on block-diagonal matrix processing. Notable computational savings and a 2.1dB OSNR increase in 40Gb/s transmission over 20 km SSMF plus 1:32 optical split were achieved with block-diagonal ZF and ML equalization, respectively. By demonstrating key benefits through efficient electronic processing, the approach is highly attractive for next-generation DSP-based optical access.

5. References

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