A Low Complexity Hybrid Time-Frequency Domain Adaptive Equalizer for Coherent Optical Receivers

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Abstract: A low complexity hybrid adaptive equalization technique, combining frequency domain filtering and multiplier-free time domain filter tap weight updates is proposed and experimentally verified. No notable penalty is observed versus the conventional time domain equalizer.
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1. Introduction

While digital coherent receivers have become the *de facto* standard for long-haul systems, direct detection is still often used in metropolitan networks due to the power consumption associated with a digital coherent receiver. Given this, there is a clear need for low complexity algorithms for digital coherent transceivers in order to reduce their power consumption. The adaptive equalizer is one of the most power consuming digital signal processing (DSP) blocks in digital coherent receivers and in this work we seek to reduce the complexity of implementation.

Generally a set of finite-impulse-response (FIR) filters connected in a 2×2 butterfly configuration are used for adaptive equalization in a coherent receiver, where tap weights are updated in time domain [1]. However, they can also be implemented in frequency domain if a large number of taps are required, for example to implement the matched filtering in the equalizer when using Nyquist pulse shaping at the transmitter [2]. Irrespective of implementing in the time or frequency domain, the complexity of the adaptive filters can be broken down into two components: (i) filtering and (ii) updating filter tap weights. As the number of taps, N, is increased, the complexity of filtering increases rapidly for time-domain implementations ($O(N)$) compared to the frequency-domain approach ($O(\log_2(N))$) [3]. On the other hand, the complexity of the tap weight updates depends of the adaptation algorithm. Recently, a multiplier free update algorithm was shown using the time domain sign-sign constant-modulus algorithm (CMA) [4, 5]. However, this algorithm is no longer multiplier free if the update is executed in the frequency domain.

In this paper, we propose a hybrid adaptive equalization technique where filtering is applied in the frequency domain using the overlap-save method and tap weights are updated in the time domain using the sign-sign CMA. Moreover, the proposed equalizer is based on block-by-block processing, which is desirable for an ASIC implementation with a low speed CMOS bus. The effectiveness of the proposed equalizer is experimentally verified with Nyquist shaped 8-GBd DP-QPSK signals, demonstrating matched filtering using the adaptive equalizer.

2. Principle of proposed equalization technique

The block diagram of the proposed equalizer is shown in Fig. 1. For ease of explanation, the filter for single polarization transmission is shown here, however this is easily extendable for the dual polarization case for the butterfly configuration used in this work. To enable a two-fold oversampled input sequence, an even-odd sub-equalizer concept [6] is considered. Thus, the time domain tap weight vector $\mathbf{h}$ of length N is separated into even and odd tap-weight vectors ($\mathbf{h}_e$ and $\mathbf{h}_o$) with $N/2$ elements. First, the two-fold oversampled input sequence is divided into even and odd sequences ($\mathbf{u}_e$ and $\mathbf{u}_o$). After parallelizing the input sequences, two $N/2$-sized blocks are concatenated (using a 50% overlap factor) and multiplied with $\mathbf{H}_e$ and $\mathbf{H}_o$ after fast Fourier transform (FFT), where $\mathbf{H}_{e,o}$ is find as $\mathbf{H}_{e,o} = \mathrm{FFT}(\mathbf{h}_{e,o})$. The filtered signal is the last block of the inverse FFT (IFFT) of summed outputs of the even and odd equalizers. Consider k (the block index), which is related to the sample index n as $n = kN + i$, $i = 0,1,\cdots N/2$. The multiplication of the error vector and the output vector, $\mathbf{v}(k)$, is calculated in time using sign-sign CMA as $\mathbf{s}(k) = \mathrm{sgn}\{1 - \mathbf{v}(k) \circ \mathbf{v}^*(k)\} \circ \mathrm{csgn}\{\mathbf{v}(k)\}$, where $\circ$ is the element-wise multiplication, superscript $(\cdot)^*$ is the complex conjugate operator and the signum function of a real-valued variable x, $\mathrm{sgn}(x)$ and a complex-valued variable z, $\mathrm{csgn}(z)$ are defined as

$$\mathrm{sgn}(x) = \begin{cases} -1 & \text{if } x < 0 \\ 1 & \text{otherwise} \end{cases} \text{ and } \mathrm{csgn}(z) = \mathrm{sgn}\{\Re(z)\} + j\,\mathrm{sgn}\{\Im(z)\}.$$

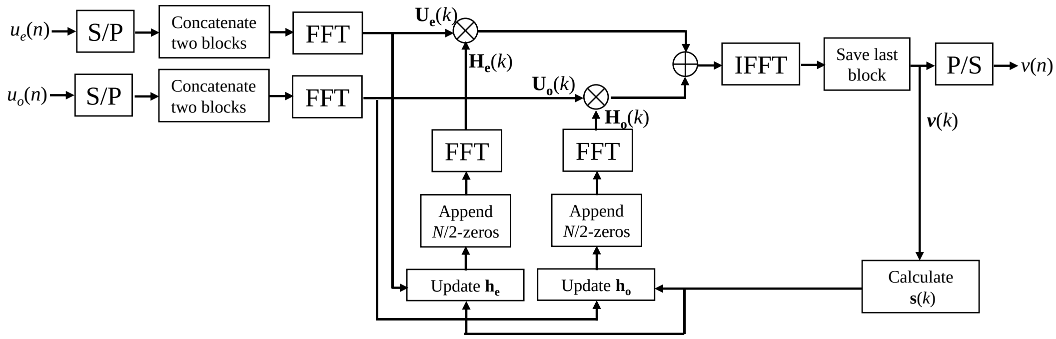

Fig. 1. Block diagram of proposed adaptive equalizer. S/P: serial-to-parallel, (I)FFT: (inverse) fast Fourier transform, P/S: parallel-to-serial.

Finally, the tap-weight vectors are updated on a block-by-block basis in the time domain as

$\mathbf{h}_{e,o}(k+1) = \mathbf{h}_{e,o}(k) + \mu \sum_{i=0}^{N-1} \mathbf{u}_{e,o}(kN+i)s(kN+i)$, where μ is the step-size parameter.

3. Complexity analysis

Considering multiplication as the most power consuming arithmetic operation in a hardware implementation [4], the computational complexity is determined by the number of complex multiplications required per DP-QPSK symbol output. In the following, the term ‘multiplication’ refers to a complex multiplication. We also neglect the cost of the CMA error term calculation, which is negligible compared to total complexity [5]. For the conventional adaptive time-domain equalization (TDE) with either the CMA or the sign-sign CMA, the complexities are 8N and 4N multiplications, respectively [4]. On the other hand, to obtain N/2 DP-QPSK output symbols in the proposed scheme, the algorithm requires 14 N-point FFTs/IFFTs and 8N multiplications for filtering whereas the update is multiplier free. Thus, total complexity is $14\log_2(N)+16$ multiplications, considering a radix-2 algorithm for FFT/IFFT implementation. Note that, if the updating is done using the CMA in the hybrid approach, we need an additional 4N multiplications for updating. Moreover, if tap weight vector updating is done also in frequency domain as in [6] using either CMA or sign-sign CMA, we need 6 N-point FFTs/IFFTs and 8N multiplications for filtering and another 18 N-point FFTs/IFFTs and 8N multiplications for updating, resulting in a total complexity of $24\log_2(N)+32$ multiplications. Table 1 summarizes the computational complexity of different approaches. Figure 2 shows the complexities of different adaptive equalization schemes in terms of the number of filter tap weights. It is found that the proposed method has significantly lower complexity than the conventional TDE using the CMA when $N \geq 16$ and even requires fewer multiplications than the sign-sign CMA when $N \geq 32$. As expected it maintains lower complexity than the hybrid CMA and the full adaptive frequency-domain equalization (FDE) using either CMA or sign-sign CMA.

TABLE-1: IMPLEMENTATION COMPLEXITY (NUMBER OF MULTIPLICATIONS PER DP-QPSK SYMBOL OUTPUT)

	Filtering		**Updating**		**Total complexity**
	Domain	**Complexity**	**Domain**	**Complexity**	
TDE (CMA)	Time	4N	Time	4N	8N
TDE (sign-sign CMA)	Time	4N	Time	0	4N
FDE(CMA)	Frequency	$6\log_2(N)+16$	Frequency	$18\log_2(N)+16$	$24\log_2(N)+32$
FDE(sign-sign CMA)	Frequency	$6\log_2(N)+16$	Frequency	$18\log_2(N)+16$	$24\log_2(N)+32$
Hybrid (CMA)	Frequency	$14\log_2(N)+16$	Time	4N	$14\log_2(N)+4N+16$
Proposed Hybrid (sign-sign CMA)	Frequency	$14\log_2(N)+16$	Time	0	$14\log_2(N)+16$

4. Simulation and experimental investigations

The simulation and experimental setup used in this work is illustrated in Fig. 3. The drive signals required for QPSK, were generated offline and filtered using a 1017-tap FIR filter having a root-raised cosine (RRC) profile with a roll-off factor of 0.01 and stop band attenuation of 30 dB. The resulting in-phase (I) and quadrature (Q) signals were output using two digital-to-analogue converters (DACs) operating at 32GSa/s (4Sa/sym) and were subsequently amplified using two linear amplifiers before

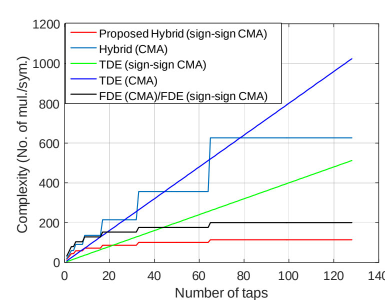

Fig. 2. Complexities of different adaptive equalization techniques versus number of filter taps.

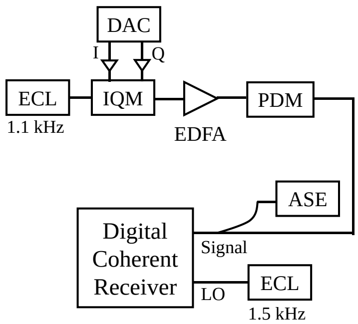

Fig. 3. Simulation and experimental configuration to investigate the performance of the proposed adaptive equalizer.

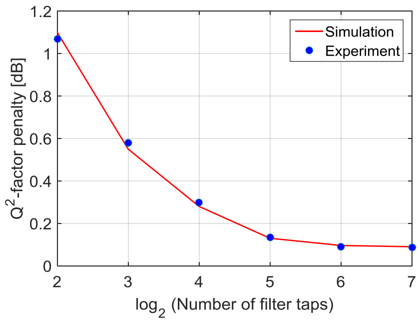

Fig. 4. Q^2-factor penalty when proposed equalizer is used to approximate matched filter response as a function of number of filter taps.

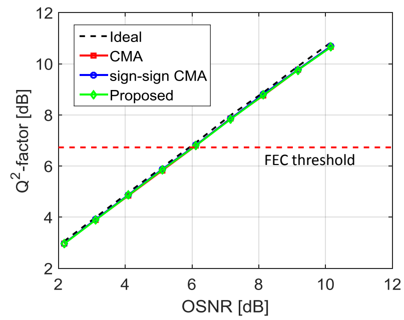

Fig. 5. Q^2-factor versus received OSNR evaluated through 8-GBd DP-QPSK experiment for different adaptive equalization approaches using N=32.

being applied to an IQ modulator. The output of an external cavity laser (ECL) with a 1.1 kHz linewidth was passed directly into the modulator before being optically amplified and polarization multiplexed to form an 8-GBd Nyquist shaped DP-QPSK optical carrier. ASE noise was added to the signal to vary the received optical signal-to-noise ratio (OSNR) and a second ECL with a 1.5 kHz linewidth was used as a local oscillator (LO). The signal was passed to the digital coherent receiver, which had a sample rate of 160 GSa/s and resampled to 2 Sa/symbol. Afterwards, the adaptive equalizer was used to apply the matched filtering and undo polarization rotations. The frequency offset (FO) was subsequently removed prior to blind carrier phase estimation (CPE). Finally, bit-error-rate (BER) is estimated and converted to Q^2-factor as $Q^2[\mathrm{dB}] = 20\log_{10}\left(\sqrt{2}\,erfc^{-1}(2\mathrm{BER})\right)$.

The Q^2-factor penalty relative to the ideal case (where a separate RRC matched filter is used prior to the adaptive equalizer) is shown in Fig. 4 as a function of number of taps when the proposed equalizer is used to approximate the matched filter response. The experimental and simulation results agree very well and it is found that to maintain a penalty below 0.2 dB, we require at least 32 taps.

Figure 5 shows the measured Q^2-factor for different adaptive equalization techniques with $N = 32$. In each case, the μ value was optimized to obtain the best Q^2-factor, however, it was always constrained to be a negative integer power of 2 so that the multiplication with μ remains multiplier free in hardware implementation (using bit-wise shift operations). It is found that the proposed scheme has similar performance compared to the conventional TDE with CMA or the sign-sign CMA, however, it has a lower complexity, as shown in Fig. 2.

5. Conclusions

A low complexity, hybrid time-frequency domain, adaptive equalization technique is presented targeting reduced power consumption for digital coherent receivers; desirable in short-reach links, such as metropolitan area networks. The performance of the equalizer is experimentally verified with a Nyquist shaped 8-GBd DP-QPSK signal and compared with other commonly used equalization techniques. Equivalent performance is observed, but with a significantly reduced computational overhead.

Acknowledgement

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