Delayed Single-tap Subband Processing for Chromatic Dispersion Compensation

Israa Slim[1], Amine Mezghani[1], Leonardo G. Baltar[1], Juan Qi[2], Fabian N. Hauske[2], Josef A. Nossek[1]

[1] *Institute for Circuit Theory and Signal Processing, Technische Universität München, D-80333, Munich, Germany*
[2] *European Research Center, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, D-80992 Munich, Germany*

israa.slim@tum.de

Abstract: Our method for subband processing frequency domain (FD) chromatic dispersion (CD) compensation is based on a single tap with delay equalizer in each subband. With this technique uncompensated trans-Pacific transmission becomes feasible.

OCIS codes: 060.1660 (Coherent communications); 060.2330 (Fiber optics communication).

1. Introduction

Long-haul transmission of 100 Gbit/s without optical chromatic dispersion (CD) compensation, i.e. without the use of dispersion compensating fiber (DCF), provides a range of benefits with respect to cost effectiveness, power budget and nonlinearity tolerance. In this case it is required to digitally compensate the CD at the transmitter (TX) or at the receiver (RX) side. This can be efficiently implemented by frequency-domain (FD) filtering to cope with the large ISI spread [1].

In state-of-the-art FD CD compensation design, the size of the fast Fourier transform (FFT) to realize fast linear convolution is governed by the specification of the maximum channel memory length with two-fold oversampling and 50% block overlap [2]. Nevertheless, the overlap-save method can be regarded not just as fast convolution method but also as a filter bank (FB) structure with trivial prototype filters and the equalization is done per subband. Our new method for subband equalization is a simple finite imulse response (FIR) equalizer where just one tap is active. This design takes into account the delay introduced in each subband exploiting the nature of the CD channel. It turns out that this approach provides much better equalization ability with no extra complexity apart from additional memory elements. In [3], the idea of subband processing with modulated FB for CD channels has been introduced. The complexity of their method as compared to ours is higher since it requires more active taps for the subband equalizer. Additionally, they considered fractional delays which leads to a non-efficient structure for the FB, whereas we consider integer delays per subband leading to an efficient implementation of the FB.

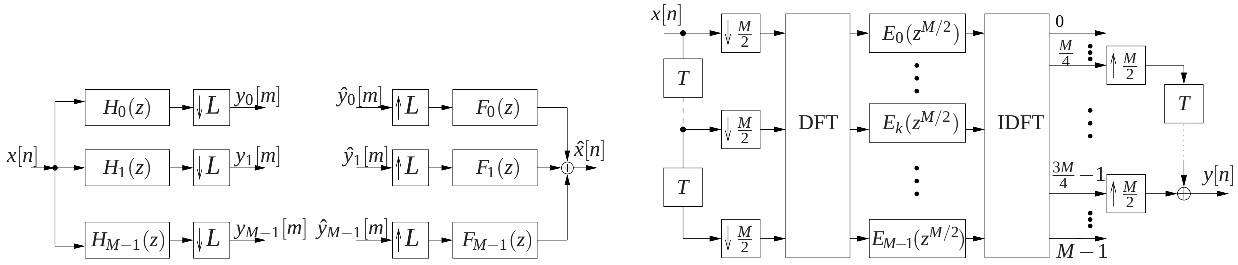
2. Single Tap with Delay Frequency Domain Equalization

2.1. *Trivial Prototype Filter FB CD Compensation*

Fig. 1(a) illustrates the general framework of a FB. We use the definition $z = e^{sT}$, where $s = \sigma + j\omega$ is the complex frequency variable. The analysis and the synthesis filters of the k-th subband are $H_k(z)$ and $F_k(z)$, respectively. The number of subbands is M and the rate changing factor is denoted as L. In general $L \leq M$. Throughout this paper, we consider the case of non-maximally decimated FB i.e. $L < M$, more specifically, we choose here $L = M/2$ even though our approach can be generalized for other values of L.

For a uniform complex modulated FB, the transfer functions of $H_k(z)$ and $F_k(z)$ are obtained by complex modulating two low-pass linear phase prototype filters $H(z)$ and $F(z)$, respectively, i.e. $H_k(z) = H(ze^{j\frac{2\pi k}{M}})$ and $F_k(z) = F(ze^{j\frac{-2\pi k}{M}})$. Both analysis and synthesis FBs can be efficiently implemented by first applying polyphase decomposition to $H(z)$ and $F(z)$ [4]. Then, some important identities for multirate processing are applied and finally the complex modulation by means of DFT and IDFT of size M is applied. The polyphase representation enables the rearrangement of computations of the filtering operations to minimize the computational load per unit time. The polyphase filters are static filters with few number of taps. To operate the FB structure as an FD equalizer, short-length FIR filters are placed between the analysis and the synthesis FBs.

The overlap-save FFT method for FD CD compensation with 50% overlap as benchmark [2] can be implemented as a non-maximally decimated DFT FB. In this case, trivial filters (i.e. rectangular impulse response) of length M and $M/2$ are chosen for $H(z)$ and $F(z)$, respectively. CD equalization is done in a per subband basis through the FIR



(a) Filter Bank: Basic Structure

(b) The method of overlap-save with 50% overlap realized as a non-maximally decimated DFT FB with trivial prototype filters and subband filter $E_k(z^{M/2})$ for CD compensation.

Fig. 1. Multirate Systems: Overlap-save method implemented as Filter Bank

filter $E_k(z)$ of length N_t. Fig. 1(b) shows the resulting structure implemented as an efficient non-maximally decimated DFT FB. Until now the case of a single tap $N_t = 1$ per subband has been considered which will be referenced as our benchmark. Our method for CD compensation is based on this non-maximally decimated DFT FB with trivial prototype filters but with single tap with delay equalizer is employed per subband, i.e. $N_t > 1$.

2.2. *Design of a Subband Single Tap with Delay Equalizer*

The idea for the single tap with delay equalizer is to take into account in the design the delay (in samples) in each subband due to the nature of the inverse of the CD channel. The group delay per subband τ_k obtained by differentiating the inverse of the channel phase response with respect to angular frequency has a linear behaviour. Now, the single tap equalizers E_k of the overlap-save method are extended to single tap with delay equalizer $E_k(z)$ with maximum number of N_t taps. To avoid any extra complexity, only one tap $e_{k,l}$ is assumed to be active performing single-tap phase equalization where the delay elements realize a subband delay. Due to the $M/2$-fold downsampling in the subband region, only a coarse (quantized) approximation of the subband group delay τ_k can be achieved. The mathematical derivation for the design of $E_k(z)$ can be found in [5]. In brief, this equalizer can be interpreted as a subband group delay filter with linear all-pass filtering of the CD in each subband.

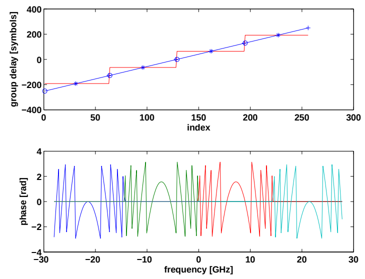
3. Simulation Results

A 28 GBaud polarization division multiplexed (PDM) return to zero (RZ) QPSK transmission with digital coherent receiver applying two-fold oversampling with 56 GS/s is used to verify our technique for CD equalization. For performance analysis, the required optical signal to noise ratio (OSNR) to tolerate different CD values (accordingly different fiber lengths) at a bit error ratio (BER) of 10^{-3} is chosen as the figure of merit. With this linear simulation model we want to demonstrate the capability of the linear equalizer. It should be noted that on top of the demonstrated filtering penalty, OSNR penalties resulting from the fiber attenuations and the according optical amplification need to be added as well as penalties from non-linearity and implementation constraints.

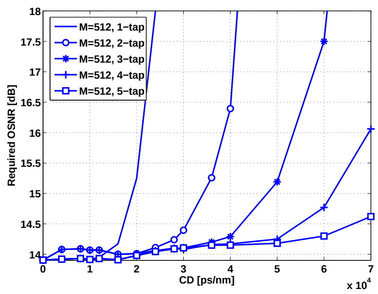
In Fig. 2(a), the quantization of the group delay and the phase response of the equalizer for the subbands is plotted for M =256, N_t = 4, and CD value of 30,000 ps/nm. The difference between the true group delay and the quantized group delay causes a low value of residual CD in each subband, which is compensated by a single-tap all-pass filtering function realizing the according parabolic phase transfer function.

In a first set of simulations, ideal synchronization of timing and carrier is assumed and only the single tap with delay FD CD compensation is applied. In Fig. 2(b), the required OSNR has been plotted for different number of taps N_t for the equalizer per subband. The advantage of a multitap equalizer can be clearly seen where significantly higher CD values are compensated for the same FFT size when increasing N_t, as long $N_t << M$. The equalizer memory can be significantly increased by the combination of the group delay elements and the phase rotation. This is a clear benefit compared to a single tap equalizer with only phase rotation. For a given maximum N_t, a lower number of active taps is automatically applied at low CD values.

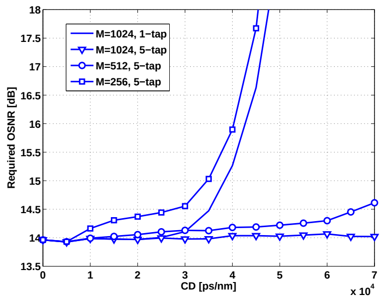
The simulations in Fig. 2(c) show the required OSNR for the same N_t but at different FFT-size M. As a benchmark, we choose the FFT size $M = 1024$ and $N_t = 1$. Significant smaller FFT sizes as compared to the benchmark for $N_t =$ 5 is needed to tolerate the same CD value. For example, to tolerate a CD value of 32,000 ps/nm, it is sufficient to have an FFT size of 256 with $N_t = 5$ with less than 1-dB OSNR penalty. With M =1024 and N_t =5, a negligible OSNR penalty is observed even outperforming the benchmark.



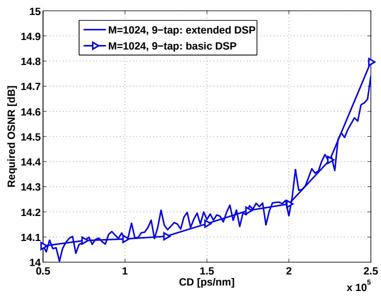
(a) group delay quantization



(b) advantage of a single tap with delay equalizer



(c) higher CD values are compensated at the cost of small penalty and additional memory elements



(d) basic CD model vs extended channel model

Fig. 2. Linear Simulations to test Single tap with Delay Equalizer

Extending the signal processing by an 11-tap ($T/2$ symbol spacing) 2x2 multi-input multi-output (MIMO) time-domain equalizer with blind convergence and acquisition by constant modulus algorithm (CMA), Viterbi & Viterbi 4-th power carrier phase estimation and carrier recovery (no differential decoding) does not largely alter the results of Fig. 2(b) and 2(c). In Fig. 2(d), the required OSNR is plotted for the extended model including CD and PMD equalization and phase recovery with $M = 1024$ and $N_t = 9$, while still assuming ideal synchronization. It is clearly seen that the results are essentially the same. For an OSNR filtering penalty of 0.5 dB more than 240,000 ps/nm can be equalized which refers to a trans-Pacific distance around 15,000 km with standard single-mode fiber.

4. Conclusion

In this work, FD CD compensation is proposed based on a non-maximally decimated DFT FB with trivial prototype filters and a multiple tap equalizer per subband. The design of the multitap equalizer takes into account the delay due to the nature of the inverse of CD channel in each subband where just one of the taps is activated while other taps are set to zero. With our design larger CD values can be compensated with a smaller FFT size by increasing the number of taps of the equalizer in each subband as long as maximum number of delay taps remains negligible as compared to the FFT size. With our technique uncompensated trans-Pacific transmission becomes feasible with digital CD compensation i.e. more than 240,000 ps/nm CD tolerance with only 0.5 dB OSNR filtering penalty can be achieved by use of 1024 FFT.

References

1. B. Spinnler, "Equalizer Design and Complexity for Digital Coherent Receivers," in *IEEE J. Quantum Electron.*, vol. 16, no. 5, pp. 1180-1192, Oct. 2010.
2. K. Ishihara *et al*, "Frequency-domain Equalization for Optical Transmission Systems," in *Electron. Lett.*, vol. 44, no. 14, pp. 870-871, Jul. 2008.
3. K.-P. Ho, "Subband Equalizer for Chromatic Dispersion of Optical Fibre," in *Electronics Letter*, vol. 45, no. 24, Nov. 2009.
4. T. Karp *et al*, "Modified DFT FBs with Perfect Reconstruction," in *IEEE Trans. on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 46, no.11, pp. 1404-1414, Nov. 1999.
5. I. Slim *et al*, "Delayed Single-tap Frequency-Domain Chromatic-Dispersion Compensation," in *IEEE Photonics Technology Letters*, vol.25, no.2, pp. 167-170, Jan. 2013.