Adaptive Compensation of Single Channel Distortions with Optical FIR-Filters at 40Gb/s

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Overview

- Adaptive Optical Distortion Compensation
  - Introduction
  - Concept of an Adaptive Optical Equalizer
  - FIR-Filter Structure

- Simulation Results: Group Velocity Dispersion, Self-Phase Modulation, Polarization Mode Dispersion, Group Delay Ripple

- Summary
Why Adaptive Distortion Compensation?

- Reconfigurable optical networks need adaptive equalization to follow the dynamic changes of the transmission channel:
  - chromatic dispersion
    - different routes through the network
    - temperature variations
  - nonlinear effects
    - signal distortions dependent on dispersion and signal power
  - PMD
    - birefringence and mode coupling variations
- **existing concepts**
  - electrical equalization by *intersymbol interference minimization* with Finite Impulse Response (FIR)-Filters, Decision Feedback Equalizer (DFE), Viterbi Equalizer
    
    *problem: envelope demodulation in the photo diode (PD)*

- optical compensation by *inverse system modeling* with e.g. DCF, CFBG, cascaded Mach-Zehnder Interferometers (MZI), Ring Resonators (RR), Etalons, VIPA

  *but: compensation of only a single fiber impairment*
Adaptive Distortion Compensation

- adaptive equalizer in the optical domain
  - equalization before the PD, phase information available
  - variable complex tap weights (el. filter: only real tap weights)
  - maximization of the electrical eye opening by controlling the tap weights of the optical filter with an adaptive algorithm

**simulation setup:**

combined optical equalization of single channel distortions
transversal structure

difficult to realize as optical filter with variable complex tap coefficients

lattice structure

cascaded Mach-Zehnder Interferometers
- lattice structure

- complex tap weights by changing the coupling and phase ratio
- the frequency response is periodic: \( FSR=1/T_d \)
  \( \Rightarrow \) combined equalization of several channels
- lattice structure
FIR - Filter Structure

- lattice structure

\[
\begin{bmatrix}
X_n(z) \\
Y_n(z)
\end{bmatrix} = \Phi_n(z) \begin{bmatrix}
X_{n-1}(z) \\
Y_{n-1}(z)
\end{bmatrix}
\]

\[
\Phi_n(z) = \begin{bmatrix}
c_n & -js_n \\
-js_n & c_n
\end{bmatrix} \begin{bmatrix}
z^{-1}e^{-j\phi} & 0 \\
0 & 1
\end{bmatrix}
\]

mit \( c_n = \sqrt{1-k_n}, \quad s_n = \sqrt{k_n}, \)

\[
\begin{bmatrix}
X_n(z) \\
Y_n(z)
\end{bmatrix} = \Phi_N \cdots \Phi_1 \Phi_0 \begin{bmatrix}
X_{in}(z) \\
Y_{in}(z)
\end{bmatrix}
\]
**40Gb/s Results - GVD**

- dispersion tolerance (1dB reference)
  - w/o equalizer: \( D = \pm 60 \text{ ps/nm} \)
  - with equalizer: \( D = \pm 200 \text{ ps/nm} \)
- arbitrary accurate equalization with increasing filter order
- equalizing performance = \( f(FSR) \)
  - increasing distortion \( \Rightarrow \) increasing pulse broadening
  - increasing FSR \( \Rightarrow \) decreasing \( T_d \) \( \Rightarrow \) shorter impulse response
  - increasing pulse broadening & shorter impulse response \( \Rightarrow \) decreasing equalization

![Graph showing eye opening penalty vs. accumulated dispersion](image)

- 40 Gb/s, linear transmission, filter order: \( n=10 \)
40Gb/s Results - SPM

- dispersion tolerance @ 9dBm
  - w/o equalizer: $D=0\text{ps/nm}$
  - with equalizer: $D = -100 \ldots +200 \text{ps/nm}$

- SPM equalization (1dB reference)
  - w/o equalizer: $P_{\text{launch}} = 9 \text{dBm}$
  - with equalizer: $P_{\text{launch}} = 12 \text{dBm}$

  ⇒ **SPM equalizing gain: 3 dB**

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40 Gb/s, nonlinear transmission, filter order: $n=10$
PMD Equalization Schemes

- Adaptive Equalization:
  - equalization with a single filter:
    - both orthogonal modes will be equalized with the same transfer function
      ⇒ slight improvement, eye cosmetics
  - equalization with 2 transfer functions:
    - by including a polarization beam splitter (PBS) both orthogonal modes see a different transfer function
      ⇒ excellent improvement
      ⇒ max $DGD_{komp} = n \cdot T_d$
40Gb/s Results - PMD 1st order

**single filter setup (filter order n=2)**

- Eye opening penalty vs. differential group delay
- **w/o equalizer**
- **γ = 0.1**
- **γ = 0.2**
- **γ = 0.3**
- **γ = 0.4**
- **γ = 0.5**

**with equalizer**

**double filter setup (filter order n=2)**

- Eye opening penalty vs. differential group delay
- **w/o equalizer**
- **γ = 0.1**
- **γ = 0.2**
- **γ = 0.3**
- **γ = 0.4**
- **γ = 0.5**

**with equalizer**
40Gb/s Results - PMD 1st and higher order

- simulated fiber span: \( L=100\text{km}, D_{\text{PMD}}=1\text{ps}/\sqrt{\text{km}}, \text{PMD}_{\text{mean}}=10\text{ps} \)

<table>
<thead>
<tr>
<th>Filter Order</th>
<th>Single Filter Setup</th>
<th>Double Filter Setup</th>
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<tbody>
<tr>
<td>( n=2 )</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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<td>( n=4 )</td>
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<td>( n=6 )</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
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Group Delay Ripple Modeling

Group Delay Measurement

Ripple Spectrum

Impulse Response

\[ t_{g,i}(\omega) = -\Delta t_{g,i} \cos \frac{\omega}{f_{\text{rip},i}} \]

\[ h_{i}(t) = \sum_{k = -\infty}^{\infty} J_{k} (\Delta t_{g,i} f_{\text{rip},i}) e^{jk\varphi_{i}} \delta_{0}(t + k / f_{\text{rip},i}) \]

\[ h(t) = h_{1}(t) \ast h_{2}(t) \ast \cdots \ast h_{1}(t) \]
GDR Equalization Schemes

- **Equalization schemes**

  - Optical inline compensation by modeling the inverse system
    
    \[ \text{CFBG + Filter = Ripple Free Device} \]

  - Post equalization with an adaptive optical filter
    
    \[ \text{Ripple mitigated tunable dispersion compensation with fixed DCFBGs} \]
40Gb/s Results - Group Delay Ripple

**Graph 1:**
- **Y-axis:** Eye opening penalty (dB)
- **X-axis:** Span count (#)
- **Legend:**
  - Black line: No filter
  - Red line: Inverse system
  - Green line: Adaptive system
- **Caption:**
  - n=10
  - n=14
  - n=18

**Graph 2:**
- **Y-axis:** Eye opening penalty (dB)
- **X-axis:** Accumulated dispersion (ps/nm)
- **Legend:**
  - Black dots: No filter
  - Red line: Inverse system
  - Green line: Adaptive system
- **Caption:**
  - Equalization of group delay ripple @ 10dBm, 2 spans, n=10
Summary

- adaptive equalizer concept:
  - excellent dispersion tolerance improvement for linear and nonlinear transmission
  - excellent SPM equalization
  - PMD equalization of 1st and higher order
  - group delay ripple compensation

combined optical mitigation of all single channel distortions