A power efficient equalizer for high speed optical communication

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Introduction & Motivation

1. Data traffic is expected to grow $5 \times$ by 2019
2. Solution is coherent optical links
3. Processing of data - DSP processing - Power hungry
4. Processing of data - Analog processing - Low power - Limited performance

Bandwidth requirement study\(^1\)

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Communication systems are greatly affected by channel interference.

Common example of channel interference are:
1. Co-channel interference
2. Inter symbol interference
3. Inter carrier interference

Coaxial cable $\rightarrow$ bandwidth limitation

Air (Cellular communication) $\rightarrow$ multipath propagation.
Need of equalization

- Intersymbol interference imposes the main obstacle in achieving increased digital transmission rates with the required accuracy.
- We can use Pre-emphasis and Rx-equalizer to overcome this obstacle.
- Pre-emphasis is done at the transmitter side.

Generally only Pre-emphasis is not used, because of not knowing much about the channel condition at transmitter.
Equalizer basics

Receiver equalizer: How equalizer works?

- Equalizer gives the inverse of channel frequency response.

\[ H_c(f) \ast H_e(f) = H(f) \]

Frequency response of channel \( H_c(f) \)

Frequency response of equalizer \( H_e(f) \)

Frequency response after the equalizer \( H(f) \)
Type of equalizers-1

Linear equalizer

- Transversal equalizers (Feed-forward filter)

\[ \text{Out}(n) = \sum_{k=0}^{N} \ln(n - k) W_k \]

- It can not work well in two conditions:
  1. Channel frequency response is zero at some frequency
  2. Channel shows very long response
Type of equalizers-2

Non linear equalizer

- Decision feedback equalizer (DFE) is a non-linear equalizer.
- It will overcome the difficulty of spectral nulls and long channel response.
- It is subtracting previously estimated bit from the current bit.
- Nullify the effect of previous bit on current bit.

- Drawback of the DFE structure → Error in the feedback loop
Equalizer basics

Transmission system using channel equalization

Equalizer can work in three modes:

1. Training mode: \( e(n) = S(n) - Y(n) \)
2. Blind mode: \( e(n) = |Y(n)| - R \)
3. Decision directed mode: \( e(n) = Y'(n) - Y(n) \)
Flow graph of equalization modes

- Training mode
- Optimum weights
- Decision directed mode

Error < E_m

No  Yes
100 Gbps DP-QPSK Optical Transmission System

100 Gb/s DP-QPSK Coherent optical communication system

Analog coherent receiver

Why analog domain signal processing have limited performance?

- Chromatic dispersion (CD) and polarization mode dispersion (PMD) → Create signal distortion → Need of equalization
- Equalization needs → Tap delay line structure
- As fiber length increases → Severe ISI → Need of more than one number of analog delay
- More than one number of analog delay → Rise to the problem of signal distortion
What are the possible solutions?
Behaviour of DFE in a training mode

Output of simple QPSK DFE

\[ x_{eq}(n) = [FF_0 \cdot x(n)] - [FB_1 \hat{s}(i - 1) + \ldots + FB_P \hat{s}(i - P)] \]

In a training mode

\[ \hat{s}(i) = s(i) \]

DFE with 0-analog delay and one digital delay
Convergence of weights in training mode

- Let consider a channel \( h = \{ h_0, h_1 \ldots h_{L-1} \} \)
- \( x(n) = h_0 s(n) + \cdots + h_{L-1} s(n - L + 1) \)
- \( x_{eq}(n) = FF_0 (h_0 s(n) + \cdots + h_{L-1} s(n - L + 1)) - (FB_1 s(n - 1) \ldots FB_P s(n - P)) \)
- For zero error weights of DFE should converge

\[
FF_0 = \frac{1}{h_0} \\
FB_i = \begin{cases} 
FF_0 \cdot h_i, & \text{if } 1 \leq i \leq P \\
0, & \text{if } i > P 
\end{cases}
\]
Behaviour of DFE in a Blind mode

- Now training data is unavailable
  \[ \hat{s}(i) \neq s(i) \]
- Open eye condition

Claim:
\[ \Theta = \{ h_0 \ h_1 \ldots h_{L-1} \in \mathbb{C}^{L-1} : \sum_{n=1}^{L-1} |h_n| < h_0 \} \]

- Channel \( \in \Theta \) will give surely convergence of weights
- But the channel \( \notin \Theta \), DFE convergence depends on number of error in feedback loop
DFE multiple minima problem

- Without training sequence DFE is not be able to converge to its desired minima
- One example of local minima is $FF_i = 0 \ \forall \ i$ 
  \[ \sum_{i=1}^{P} |FB_i| = 1 \]
- Convergence is depends on weight initialization and impulse response of the channel
DFE equalizer transfer function

- DFE equalizer transfer function
  \[ H_{DFE}(f) = \frac{H_{FF}(f) \cdot 2\pi f_i}{H_{FB}(f) + 2\pi f_i} \]

- Linear equalizer transfer function
  \[ H_{LE}(f) = \frac{1}{H_c(f)} \]

- Spectral null problem
  \[ X(f) = S(f) \cdot H_c(f) + N(f) \]
  \[ X_{eq}(f) = S(f) \cdot H_c(f) \cdot H_{eq}(f) + N(f) \cdot H_{eq}(f) \]
  \[ = 0 \text{ if } H_c(f) = 0 \]

- Spectral null problem can be solved by the transfer function of DFE.
DFE gives solution of spectral null

- Result derive in time domain analysis
  \[
  FF_0 = \frac{1}{h_0}
  \]
  
  \[
  FB_i = \begin{cases} 
  FF_0 \cdot h_i, & \text{if } 1 \leq i \leq P \\ 
  0, & \text{if } i > P 
  \end{cases}
  \]

- Using these results feedback transfer function can be derive in terms of channel transfer function
  \[
  H_{FB}(f) = \frac{H_c(f)}{h_0} - 1
  \]
  
  \[
  H_{DFE}(f) = \frac{2\pi fi}{H_c(f) - h_0 + 2\pi fi \cdot h_0} < \infty
  \]
Output of MIMO DFE can be written as

\[ x_{eq} = FF_{xx}^T \bar{x} + FF_{yx}^T \bar{x} - FB_x^T \hat{s}_x \]
\[ y_{eq} = FF_{yy}^T \bar{y} + FF_{xy}^T \bar{x} - FB_y^T \hat{s}_y \]

(1)

Weight Updates

\[ FF_{xx} = FF'_{xx} + \mu e_x \bar{x} \]
\[ FF_{xy} = FF'_{xy} + \mu e_y \bar{x} \]
\[ FF_{yx} = FF'_{yx} + \mu e_x \bar{y} \]
\[ FF_{yy} = FF'_{yy} + \mu e_y \bar{y} \]
\[ FB_x = FB'_{x} + \mu e_x \hat{s}_x \]
\[ FB_y = FB'_{y} + \mu e_y \hat{s}_y \]

(2)
Results of DFE in a blind mode - 5 km Fiber length

Received constellation

Constellation after equalizer

Weights settlement

Error signal
Results of DFE in a blind mode - 15 km Fiber length

![Constellation Plots for 12.5 Gb/s and 25 Gb/s](image)

- **12.5 Gb/s constellation**
  - Output constellation
  - Error

- **25 Gb/s constellation**
  - Output constellation
  - Error

![Weights Settlement Graph](image)
Results of DFE in a training mode - BER vs Fiber length & BER vs OSNR

DFE consists of 0 analog delay and 1 digital delay
Feedforward equalizer consists of 1 analog delay
Results of DFE in a blind mode - BER vs Fiber length & BER vs OSNR

DFE consists of 0 analog delay and 1 digital delay
Feedforward equalizer consists of 1 analog delay

![Graph showing BER vs fiber length and BER vs OSNR for DFE-Blind and CMA methods.](image)

BER Vs Fiber length (km)

BER Vs OSNR (dB)
DFE complexity comparison

Table: Summary of computational complexity of different Equalization schemes

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Multiplications</th>
<th>Additions</th>
<th>Sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMS</td>
<td>40N</td>
<td>32N + 4</td>
<td>-</td>
</tr>
<tr>
<td>CMA</td>
<td>40N + 4</td>
<td>32N + 8</td>
<td>-</td>
</tr>
<tr>
<td>DFE</td>
<td>40N + 40P</td>
<td>32N + 32P + 12</td>
<td>4</td>
</tr>
</tbody>
</table>

Complexity of DFE increases at the order of $O(N + P)$
Complexity feedforward equalizer increases only at the order of $O(N)$
Power consumption comparison

- Power consumption by CMA equalizer (Considering 1 analog delay cell)\(^1\)
  \[ P_{CMA} = 60 \times 4 = 240\,mW \]

- Power consumption by DFE equalizer (Considering 0 analog delay cell + 1 digital delay cell) \(^2\)
  \[ P_{DFE} = 12 \times 2 = 24\,mW \]

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\(^1\)P.K. Moyade et.al, VLSI Design (VLSID), 2012.
Time and frequency domain analysis of feedback equalization have been presented.

Unique strategy has been presented to work conventional DFE in a blind mode.

In simulation results we also present behavior of DFE on NZDSF fiber which is very non linear in nature compare to other fibers. On NZDSF fiber DFE is outperform than other linear feed forward equalizers.
Facebook wants 100 Gb/s receiver

Facebook Likes 100G at $1/G

Web giant plans 2016 Ethernet upgrade

Rick Merritt
8/28/2015 11:50 AM EDT
2 comments

SANTA CLARA, Calif. – Facebook helped define a low cost 100 Gbit/second optical Ethernet transceiver it expects to start deploying next year. The move is another example of ways big data centers are driving design in computers and networking.

Facebook specified a 100G transceiver using single-mode fiber it believes it can drive to a cost of $1/Gbyte. To hit the lower costs it relaxed distance requirements to 500 meters down from 2km and eased specs on operating temperature and product lifetime.

The transceivers are based on QSFP28, a pluggable form factor which uses four 25Gbit/second lanes. They also leverage the
Thank You!!!