A power efficient equalizer for high speed optical communication

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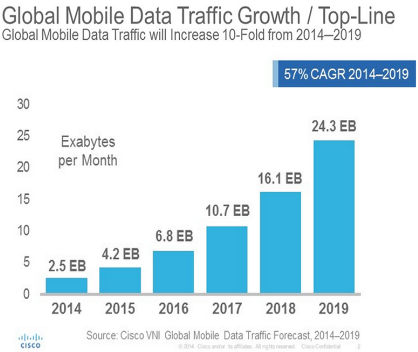
October 15, 2015

Introduction & Motivation

1. Data traffic is expected to grow 5× 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

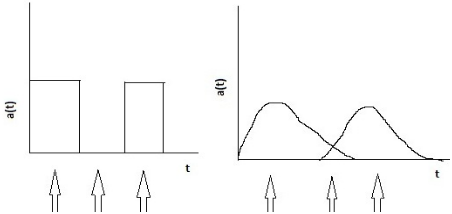


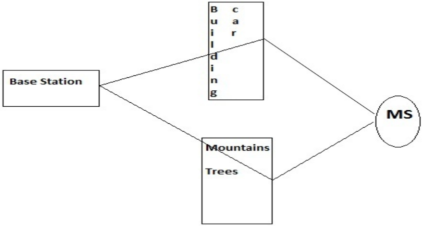
Bandwidth requirement study[1]

1- Cisco visual networking index: Forecast and methodology, 2013-2018, Cisco, White Paper,Jun.2014.

Explanation of ISI and multipath propagation

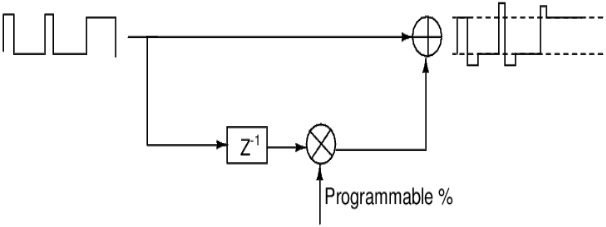
- Communication systems are greatly affected by channel interference.
- Common example of channel interference are:
  1. Co-channel interference
  2. Inter symbol interference
  3. Inter carrier interference
- Coaxial cable $\rightarrow$ bandwidth limitation
- Air(Cellular communication) $\rightarrow$ multipath propagation.





Need of equalization

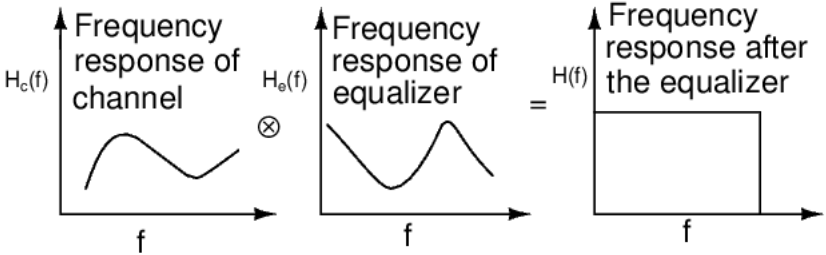
- Intersymbol interference imposes the main obstacle in achieving increased digital transmission rates with the required accuracy
- We can use Pre-emphasis and Rx-equalizer to overcome this obstacle.
- Pre-emphasis is done at the transmitter side



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

Receiver equalizer: How equalizer works ?

- Equalizer gives the inverse of channel frequency response.



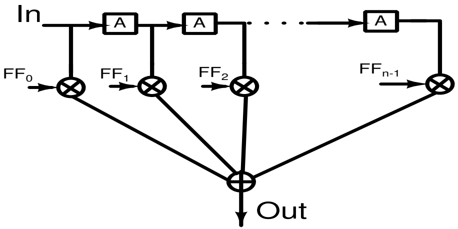
Type of equalizers-1

Linear equalizer

- Transversal equalizers (Feed-forward filter)

$$Out(n) = \sum_{k=0}^{N} In(n-k)W_k$$

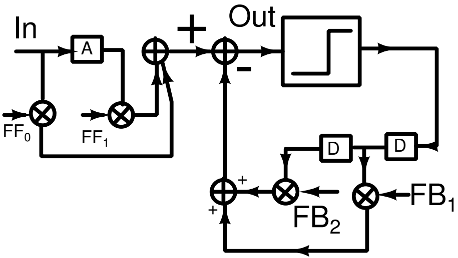
- It can not work well in two conditions:
    1. Channel frequency response is zero at some frequency
    2. Channel shows very long response



Type of equalizers-2

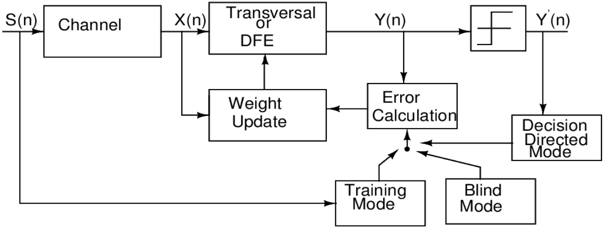
Non linear equalizer

- 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

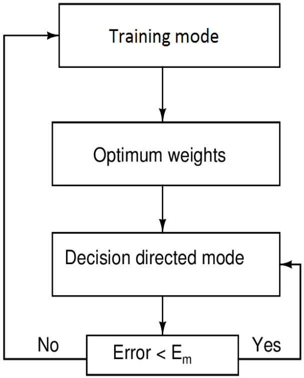
Transmission system using channel equalization



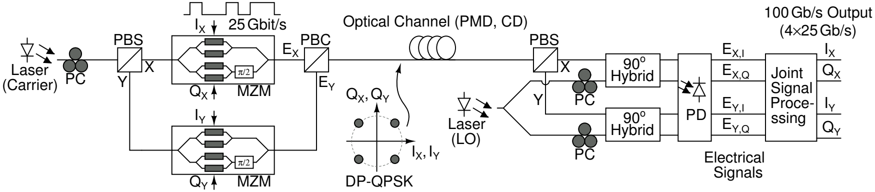
Equalizer can work in three modes:

1. Training mode: $e(n) = S(n) - Y(n)$
2. Blind mode: $e(n) = |Y(n)| - R$
3. Decision directed mode: $e(n) = Y'(n) - Y(n)$

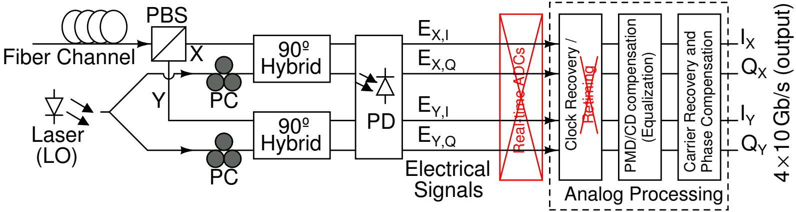
Flow graph of equalization modes



100 Gbps DP-QPSK Optical Transmission System



100 Gb/s DP-QPSK Coherent optical communication system[1]



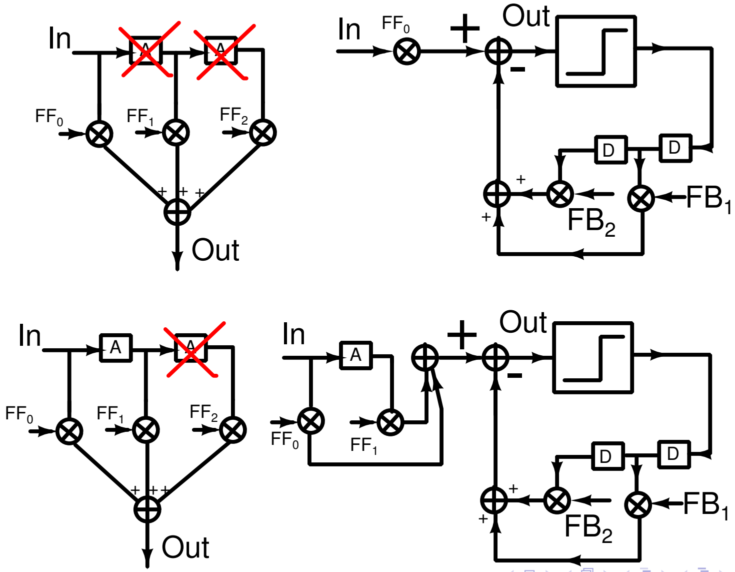
Analog coherent receiver[1]

N. Nambath et al, IEEE/OSA Journal of Lightwave Technology, 2015

Why analog domain signal processing have limited performance ?

- Chromatic dispersion (CD) and polarization mode dispersion (PMD) $\rightarrow$ Create signal distortion $\rightarrow$ Need of equalization
- Equalization needs $\rightarrow$ Tap delay line structure
- As fiber length increases $\rightarrow$ Severe ISI $\rightarrow$ Need of more than one number of analog delay
- More than one number of analog delay $\rightarrow$ Rise to the problem of signal distortion

What are the possible solutions ?



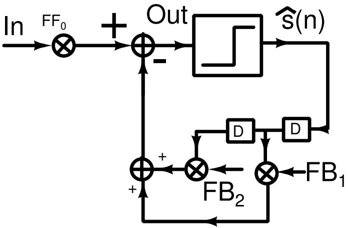
Behaviour of DFE in a training mode

1. Output of simple QPSK DFE

$$x_{eq}(n) = [FF_0 x(n)] - \underbrace{[FB_1 \hat{s}(i-1) + ... + FB_P \hat{s}(i-P))]}_{FB^T \hat{s}}$$

2. In a training mode

$$\hat{s}(i) = s(i)$$



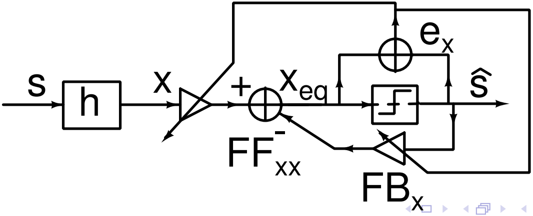
DFE with 0-analog delay and one digital delay

Convergence of weights in training mode

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

$$FF_0 = \frac{1}{h_0}$$

$$FB_i = \begin{cases} FF_0.h_i, & \text{if } 1 \leq i \leq P \\ 0, & i > P \end{cases}$$



Behaviour of DFE in a Blind mode

- Now training data is unavailable

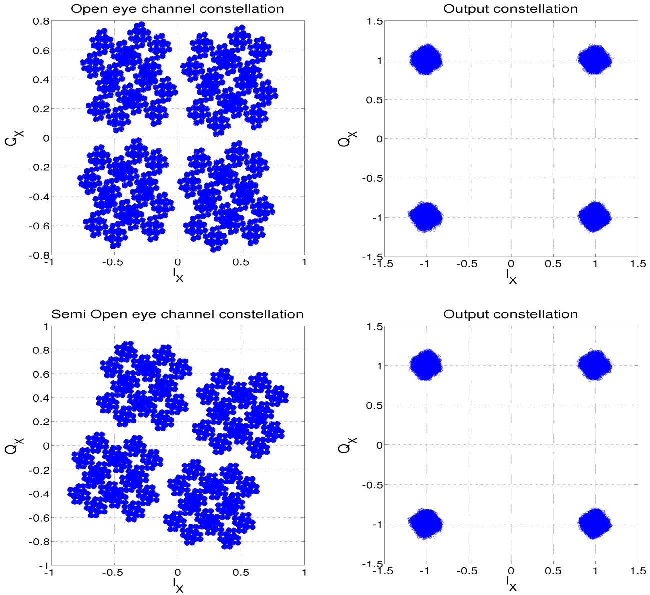
$$\hat{s}(i) \neq s(i)$$

- Open eye condition

Claim:

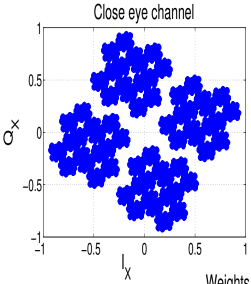
$$\Theta = \{h_0 \; h_1 \ldots h_{L-1} \in \mathbb{C}^{L-1} : \sum_{n=1}^{L-1} |h_n| < h_0\}$$

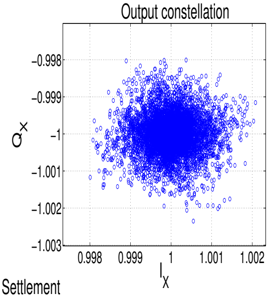
- Channel $\in \Theta$ will give surely convergence of weights
- But the channel $\notin \Theta$, DFE convergence depends on number of error in feedback loop

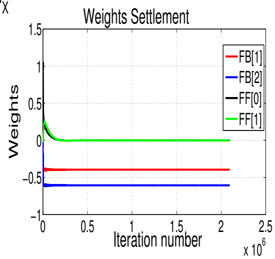

Open eye channel constellation
Output constellation
Semi Open eye channel constellation
Output constellation
Q_X
I_X

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

$$H_{DFE}(f) = \frac{H_{FF}(f).2\pi fi}{H_{FB}(f)+2\pi fi}$$

- Linear equalizer transfer function

$$H_{LE}(f) = \frac{1}{H_c(f)}$$

- Spectral null problem

$$X(f) = S(f).H_c(f) + N(f)$$
$$X_{eq}(f) = \underbrace{S(f).H_c(f).H_{eq}(f)}_{=0 \text{ if } H_c(f)=0} + N(f)H_{eq}(f)$$

- Spectral null problem can be solved by the transfer function of DFE

DFE gives solution of spectral null

- Result derive in time domain analysis

$$FF_0 = \frac{1}{h_0}$$

$$FB_i = \begin{cases} FF_0.h_i, & \text{if } 1 \leq i \leq P \\ 0, & i > P \end{cases}$$

- Using these results feedback transfer function can be derive in terms of channel transfer function

$$H_{FB}(f) = \frac{H_c(f)}{h_0} - 1$$

$$H_{DFE}(f) = \frac{2\pi fi}{H_c(f) - h_0 + 2\pi fi.h_0} < \infty$$

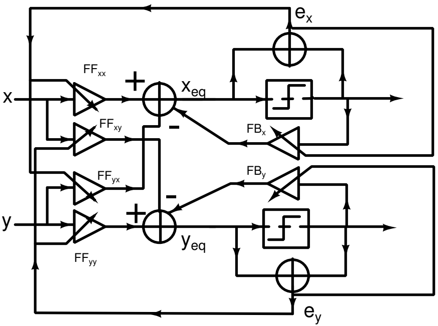
DFE for DP-QPSK System

1. Output of MIMO DFE can be written as

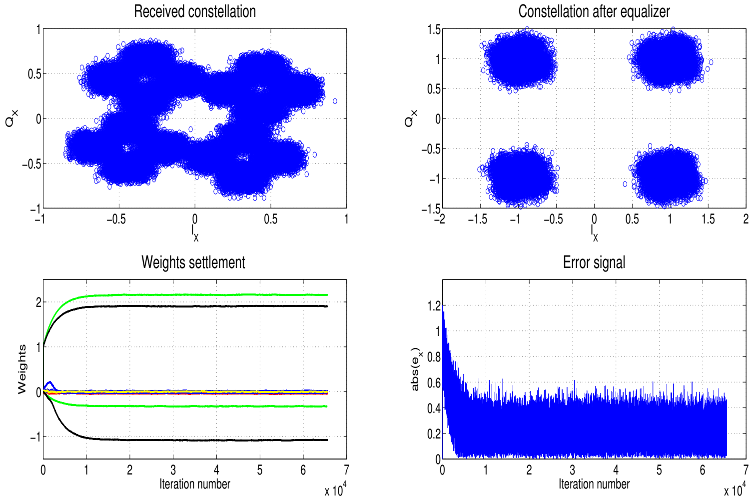
$$x_{eq} = FF_{xx}^T\bar{x} + FF_{yx}^T\bar{x} - FB_x^T\bar{\hat{s}}_x$$
$$y_{eq} = FF_{yy}^T\bar{y} + FF_{xy}^T\bar{x} - FB_y^T\bar{\hat{s}}_y \quad (1)$$

2. Weight Updates

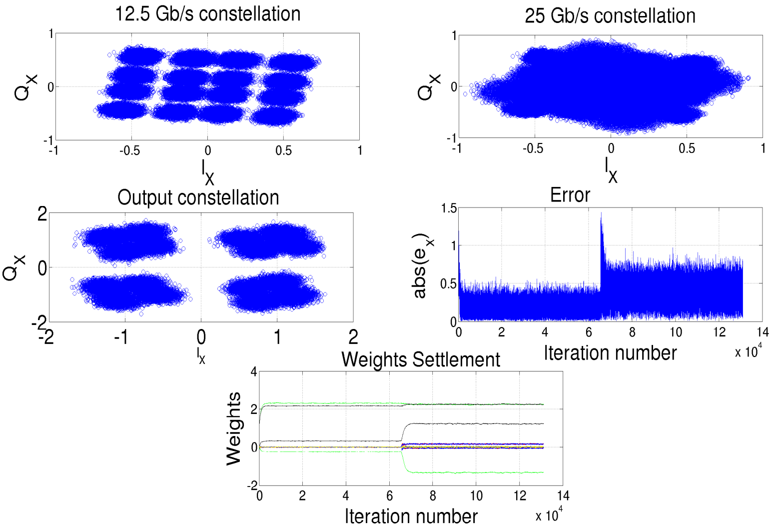
$$\begin{aligned} FF_{xx} &= FF_{xx}^{'} + \mu e_x\bar{x} \\ FF_{xy} &= FF_{xy}^{'} + \mu e_y\bar{x} \\ FF_{yx} &= FF_{yx}^{'} + \mu e_x\bar{y} \\ FF_{yy} &= FF_{yy}^{'} + \mu e_y\bar{y} \\ FB_x &= FB_x^{'} + \mu e_x\bar{\hat{s}}_x \\ FB_y &= FB_y^{'} + \mu e_y\bar{\hat{s}}_y \end{aligned} \quad (2)$$



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



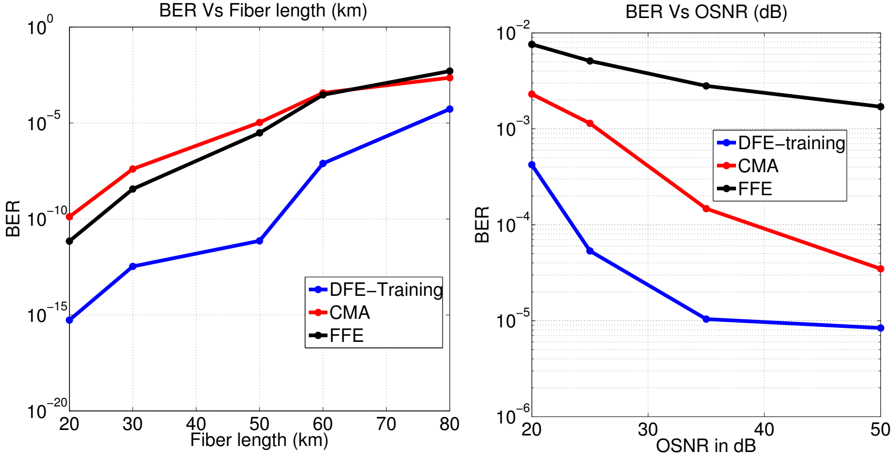
Results of DFE in a blind mode - 15 km Fiber length



Results of DFE in a training mode - BER vs Fiber length & BER vs OSNR

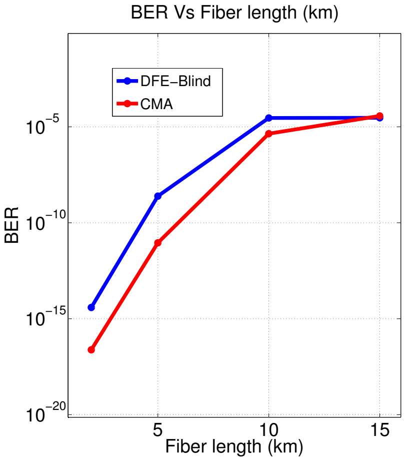
DFE consists of 0 analog delay and 1 digital delay

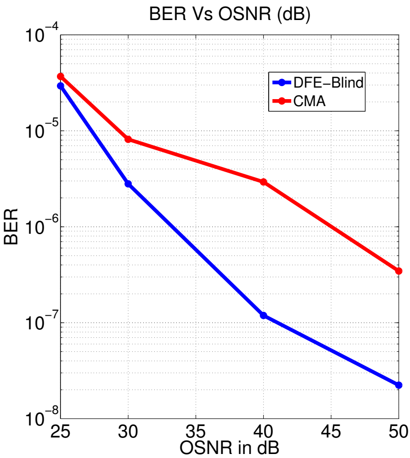
Feedforward equalizer consists of 1 analog delay



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





DFE complexity comparison

Table : Summary of computational complexity of different Equalization schemes

Algorithm	Multiplications	Additions	Sign
LMS	40N	32N + 4	-
CMA	40N + 4	32N + 8	-
DFE	40N + 40P	32N + 32P + 12	4

Complexity of DFE increases at the order of $\mathcal{O}(N+P)$
Complexity feedforward equalizer increases only at the order of $\mathcal{O}(N)$

Power consumption comparison

- Power consumption by CMA equalizer (Considering 1 analog delay cell)[1]

$$P_{CMA} = 60 \times 4 = 240mW$$

- Power consumption by DFE equalizer (Considering 0 analog delay cell + 1 digital delay cell)[2]

$$P_{DFE} = 12 \times 2 = 24mW$$

[1] P.K. Moyade et.al, VLSI Design (VLSID), 2012.

[2] U.Singh, Green, M.M., JSSC, 2005.

Conclusion

- 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

designlines WIRELESS & NETWORKING

News & Analysis

Facebook Likes 100G at $1/G

Web giant plans 2016 Ethernet upgrade

Rick Merritt

8/28/2015 11:50 AM EDT

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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!!!