Nonlinearity Equalization Techniques for DML-Transmission Impairments

Johannes von Hoyningen-Huene

jhh@tf.uni-kiel.de

Christian-Albrechts-Universität zu Kiel

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Motivation

Future Optical Access Networks need to be cost efficient!

• Only low-cost optical components
  → DML (direct modulated laser), Direct Detection, no DCF, no external modulators,…

• Thus limited performance
  → at high-speed, longer distance, high customer count,…

• Electronic signal processing (cheap CMOS!) may help to overcome these performance limitations

• We compensate and equalize for impairments of low-cost optics by sophisticated electronic processing
  → DML nonlinearity and chirp, DD nonlinearity, limited bandwidth, …

Goal: Squeeze maximum performance (e.g. 10Gbit/s, 100km) from low cost optical equipment (e.g. 2.5Gbit/s DML, DD,…)

Outline

1. Motivation

2. Nonlinear Distortions in Access

3. Post-Compensation at Receiver Side
Distortions in Access Networks

Laser/Modulator
- Low cost DML
- Chirp
- Low bandwidth

Fiber
- Long distance
- e.g. 100km

Optical Front End
- Direct Detection

OLT
- downlink
- Tx
- uplink
- Rx

AWG
- 1:N

ONU
- downlink
- Rx
- uplink
- Tx

Question:
Can we design 10Gb/s NGA from 2.5Gb/s optics
- 40Gb/s
- 10Gb/s
- , etc?
Distortions from DML (Direct Modulated Laser)

Rate Equations: Model for DML

\[ \frac{dN}{dt} = \frac{I}{eV} - \frac{N(t)}{\tau_n} - g_0 \left( N(t) - N_t \right) \frac{S(t)}{1 + \varepsilon \cdot S(t)} \]

\[ \frac{dS}{dt} = \Gamma g_0 \left( N(t) - N_t \right) \frac{S(t)}{1 + \varepsilon \cdot S(t)} + \frac{\beta \Gamma N(t)}{\tau_n} - \frac{S(t)}{\tau_p} \]

\[ \frac{d\phi}{dt} = \frac{\alpha}{2} \left[ \Gamma g_0 \left( N(t) - N_t \right) - \frac{1}{\tau_p} \right] \]

System with memory: limited bandwidth
IM: nonlinear
FM/PM: chirp

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) modulation current</td>
<td>0-100 mA</td>
</tr>
<tr>
<td>(N) carrier density</td>
<td></td>
</tr>
<tr>
<td>(S) photon density</td>
<td></td>
</tr>
<tr>
<td>(V) active volume</td>
<td>(3.22 \cdot 10^{-3} \text{ m}^3)</td>
</tr>
<tr>
<td>(g_0) gain</td>
<td>(4.71 \cdot 10^{-12} \text{ m}^3/\text{s})</td>
</tr>
<tr>
<td>(N_t) carrier density at transparency</td>
<td>(6.50 \cdot 10^{23} \text{ m}^{-3})</td>
</tr>
<tr>
<td>(\beta) fraction of spontaneous emission</td>
<td>(2.46 \cdot 10^{-4})</td>
</tr>
<tr>
<td>(\Gamma) mode confinement factor</td>
<td>0.224</td>
</tr>
<tr>
<td>(\tau_p) photon lifetime</td>
<td>(3.22 \cdot 10^{-3} \text{ m}^3)</td>
</tr>
<tr>
<td>(\tau_e) electron lifetime</td>
<td>(7.03 \cdot 10^{-12} \text{ s})</td>
</tr>
<tr>
<td>(\phi) optical phase</td>
<td></td>
</tr>
<tr>
<td>(\alpha) linewidth enhancement factor</td>
<td>2</td>
</tr>
</tbody>
</table>

\[ P(t) e^{\Delta \Phi} \rightarrow \text{fiber} \]

\[ \int_{\Delta f} \int_{\Delta \Phi} \]
DML Characterization

DC – characterisation
Bookham LC25W5898BA-C34

- Parameters of rate equations fitted to measurement
- DML behavior depends strongly on bias current
- 3 GHz LPF to allow for laser packaging

Comparison: measurement/simulation

RF - characterisation

Bias = 10 mA

Bias = 24 mA

Parameters of rate equations fitted to measurement

DML behavior depends strongly on bias current

3 GHz LPF to allow for laser packaging
DML Characterization

2.5 Gb/s

5 Gb/s

10 Gb/s

100km no chirp (“switched off“)

Chirp + dispersion destroy the eye!

3dBm, Bias 21.5 mA 20mAmp

Impairments from DML, Fibre & Direct Detection

- **Laser/Modulator**
  - DML with nonlinear intensity modulation
  - Chirp
  - Limited bandwidth

- **Fibre (SSMF)**
  - with loss and dispersion
  - (Kerr-Nonlinearity neglected here)

- **Direct Detection at Receiver**
  - Loss of phase by $|...|^2$ operation
  - Nonlinear transducer from opt. to electr.
  - Limited bandwidth

Different Impairments in Access and Long-haul!
Equalizer Types for Linear Distortions

- **Feed-Forward-Equalizer (FFE)**

  \[ y_{FFE}(t) = \sum_{n=0}^{N} e_n y(t - n \cdot T_A) \]

- **Decision-Feedback-Equalizer (DFE)**

  \[ y_{DFE}(k \cdot T_A) = y(k \cdot T_A) - \sum_{n=1}^{N_b} b_n \hat{d}((k - n) \cdot T_A) \]

Goal: Recover symbols (maximize eye opening)
Equalizers for Nonlinear Distortions

**Nonlinear FFE**

\[ y_q(k \cdot T_s) = \sum_{n=0}^{n_e} y(k \cdot T_s - n \cdot T_A) \cdot e_n \]

**FFE (linear)**

\[ -\sum_{n=1}^{n_b} d(k - n) \cdot b_n \]

**DFE (linear)**

\[ + \sum_{n=0}^{n_e} \sum_{m=n}^{n_e} y(k \cdot T_s - n \cdot T_A) \cdot y(k \cdot T_s - m \cdot T_A) \cdot e_{nm} \]

**FFE quadratic**

\[ -\sum_{n=1}^{n_b} \sum_{m=n+1}^{n_b} d(k - n) \cdot d(k - m) \cdot b_{nm} + \ldots \]

**DFE quadratic**
Equalizer Types

Maximum-Likelihood-Sequence-Estimator (MLSE)

\[ L_\mu = \sum_{k=0}^{L} |y(k) - g(k) * d_\mu(k)| = \min \Rightarrow d_\mu \]

→ Select data sequence \( d_\mu \) of limited length, whose channel response most fits to received signal.

Efficient implementation with Viterbi Algorithm

Goal: Recover data sequence
Estimation of Equalizer Coefficients

- Training sequence, which is known to the receiver
  - FFE-DFE: Estimation with Minimum-Mean-Square Error
  - MLSE: Retrieve mean PDF for different trellis branches

- Adaptive blind optimization of coefficients possible.

- No return pass required for coefficients estimation

- Equalizer design parameters
  - Equalizer processing speed (in terms of samples per data bit)
  - Equalizer memory (in terms of number of coefficients or trellis depth)
Simple transmitter: bit pattern generator+DML
no knowledge about channel required
no DSP required

Complex receiver: ADC required
DSP for clock recovery, channel estimation and EQ
Linear vs. Nonlinear: FFE/DFE

- Great advantage with nonlinear FFE
- Minor advantage with nonlinear DFE
  reason: reduced value set after slicer in DFE
- **FFE/DFE \( \rightarrow \) nlin/lin = best option

Experimental:
100+50 km,
Bias=30 mA,
Performance depend. on EQ-Length & DML Power

1 sample/bit

\[ \log_{10}(BER) \]

-8 dBm
-10 dBm
-12 dBm

FFE/DFE nlin / lin

2 samples/bit

\[ \log_{10}(BER) \]

-8 dBm
-10 dBm
-12 dBm

FFE/DFE-Memory

MLSE

\[ \log_{10}(BER) \]

-8 dBm
-10 dBm
-12 dBm

MLSE-Memory

Experimental:
10 Gb/s, 100+50 km, Bias=30 mA
Measured Signal after lin. and nonlin. EQ, B2B

- B2B: no advantage with nonlin. EQ

bias = 30 mA,
opt. launch power: 5.5 dBm,
10Gb/s
1 sample/bit

→ B2B: no advantage with nonlin. EQ
Dispersive channel: great benefit with nonlin. EQ

We compensate for nonlinearities: chirp and DD envelope detection!
Acknowledgement

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