Coherent polarization-multiplexed formats: receiver requirements and mitigation of fiber non-linear effects

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Motivation

- Multi-level modulation with coherent detection are clearly becoming the enabling solution for future high capacity long-haul system.

- A key component in such systems is the ADC: relaxing the requirements will be beneficial reducing costs, complexity and power consumption.

- Fiber non-linear effects are limiting the maximum reach but coherent detection offers new opportunities for mitigating the impact.
1. TX and RX set-up
2. Receiver requirements
3. Mitigation of fiber non-linear effects
4. Conclusions
1. TX and RX set-up
Simulation parameters

- Symbol rate
  - 25 Gbaud + 11% overhead: 27.75 Gbaud

- Three modulation formats:
  - PM-QPSK \(\Rightarrow\) 111.0 Gbps (100 Gbps)
  - PM-8QAM \(\Rightarrow\) 166.5 Gbps (150 Gbps)
  - PM-16QAM \(\Rightarrow\) 222.0 Gbps (200 Gbps)

- Channel spacing
  - \(\Delta f = 50\) GHz

- Simulation details
  - Independent PRBSs for each tributary (degree 16)
  - BER evaluation based on error counting
  - Reference BER = \(4 \cdot 10^{-3}\)
  - Fiber propagation: full band split-step method
Transmitter

- Based on Nested Mach-Zehnder for QPSK and 16QAM
  - Binary driving for QPSK
  - Four level driving with pre-distortion for 16QAM
- Two cascaded Nested Mach-Zehnders for 8QAM
Common opto-electronic front-end for all formats
- When ADC speed is reduced below 2 SpS, then up-sampling is performed to run DSP at 2 SpS
- Ideal clock recovery
- Ideal EDC
Equalizer updating and Symbol decision

- MIMO Equalizer
  - Ideal FIR with 15 taps
  - Updated through LMS
    - Training + Decision Driven
- Decision algorithms are specific for each format
  - PM-QPSK: single-threshold
  - PM-8QAM: maximum likelihood
  - PM-16QAM: multi-threshold
2. Receiver requirements
Optimization setup

Optimal bandwidths of both Optical MUX and Electrical receiver filter are dependent on ADC parameters.
After propagation, signal components have a gaussian-like distribution (see [A] P4.07 at ECOC 2010)

We define as clipping percentage the portion of samples left out of the ADC quantization range

We performed preliminary simulation in order to optimize the clipping percentage.

For all formats, in the range between 0.1% and 2%, performances do not change substantially at reference BER \((4 \cdot 10^{-3})\).

For bandwidth optimization and non-linear analysis we have used the following clipping percentages:
- 0.5% for PM-QPSK
- 0.2% for both PM-8QAM and PM-16QAM
For each modulation format

- ADC Speed $\Rightarrow$ SpS=$[2.00 \ 1.67 \ 1.43 \ 1.25 \ 1.11]$
- ADC Resolution $\Rightarrow$ $N_{bit}=[4 \ 5 \ 6 \ 7]$

**Optimization map**

Contour plot of OSNR (in 0.1 nm) required to guarantee BER=$4\cdot10^{-3}$

- **PM-QPSK**
  - $SpS=1.25$
  - $N_{bit}=4$

- $B_{TX,\text{opt}}=33$ GHz
- $B_{RX,\text{elt}}=9.8$ GHz
Bandwidths optimization results did not show any dependence on ADC resolution

Reducing ADC speed introduces aliasing in the system, that can be neutralized with tighter filtering
Back-to-Back performance

- We measured the OSNR (in 0.1 nm) required to guarantee BER=4⋅10^{-3}

![Graph showing OSNR vs. Samples per symbol for different modulation formats (PM-8QAM, PM-QPSK, PM-16QAM).](image)

- Ideal ADC
  - Osnr = 19.0 dB
  - 1.25 SpS ≈ 35 GSa/s

<table>
<thead>
<tr>
<th>Modulation</th>
<th>OSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-8QAM</td>
<td>16.1</td>
</tr>
<tr>
<td>PM-QPSK</td>
<td>12.1</td>
</tr>
<tr>
<td>PM-16QAM</td>
<td>19.0</td>
</tr>
</tbody>
</table>
What if you do not properly optimize?

- Bandwidths optimized at SpS=2.00
- Bandwidths optimized at SpS=1.25

ADC resolution $N_{\text{bit}}=7$

0.75 dB @ SpS=1.25
Maximum reach evaluation

- Uncompensated link
- Span budget: 25 dB
- Optimal filter bandwidths
- We look for maximum reach at BER target, optimizing the launch power

**Diagram Details:**
- **SFM fiber**
  - $D=16.7 \text{ ps/nm/km}$
  - $\alpha=0.22 \text{ dB/km}$
  - $\gamma=1.3 \text{ 1/W/km}$

- **EDFA**
  - $F=6 \text{ dB}$

**Components:**
- **MUX**
- **90 km SSMF**
- **VOA**
- **EDFA**
- **Rx**

**WDM**
- $\Delta f=50 \text{ GHz}$
Optimum launch power is not dependent on ADC speed and resolution.
Maximum reach comparison

Reach reduction is only due to poorer back-to-back performance

Assuming to work with SpS=1.25 and using $N_{bit}=5$ we get:

<table>
<thead>
<tr>
<th></th>
<th>Capacity in C band [Tbps]</th>
<th>Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Span</td>
</tr>
<tr>
<td>PM-QPSK</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>PM-8QAM</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>PM-16QAM</td>
<td>16</td>
<td>6</td>
</tr>
</tbody>
</table>

1.25 SpS ≈ 35 GSa/s

Ideal ADC
DSP running at 1.25 SpS

Equalizer update performed only on RED points:
- at 2 SpS EQ is updated every 2 samples
- at 1.25 SpS EQ is updated every 5 samples
DSP running at 1.25 SpS: penalty?

- **Back-to-Back performance**
  - **Sampling at 1.25 SpS**
    - with DSP running at 2.00 SpS \( \Rightarrow 12.25 \text{ dB} \)
    - with DSP running at 1.25 SpS \( \Rightarrow 12.40 \text{ dB} \)
    - **0.15 dB penalty**

- Maximum Reach with 7 bit ADC resolution is 35 spans in both cases
3. Mitigation of non-linear effects
Coherent receiver can take advantage of DSP also to compensate for non-linear effects

Several approaches: all very effective on single channel

Complexity is a major issue...

**PM-QPSK**
- Backward Propagation (1 step per span)
  - 1CH
  - Improve from 52 to 72 spans → 1.4 dB

**WDM**
- Improve from 39 to 47 spans → 0.8 dB
Dispersion management

- EDC is set to fully compensate total residue
- Pre-compensation does not give any substantial advantage (see [B]) \( D_{\text{pre}} = 0 \) ps/nm
- We carried out joint launch power and in-line residue \( (D_{\text{res,IL}}) \) optimization, looking for maximum Span Budget

Contour plot of Span Budget giving BER=\(4 \cdot 10^{-3}\)

PM-QPSK - \(N_{\text{span}}=39\)

Without DCU
\(D_{\text{res,IL}}=\text{DL}\)
Contour plot of Span Budget

PM-8QAM - $N_{\text{span}} = 14$

PM-16QAM - $N_{\text{span}} = 7$

Without DCU
$D_{\text{res,IL}} = DL$

Without DCU
$D_{\text{res,IL}} = DL$
New fibers, PSCF in particular, show lower $\gamma$, lower $\alpha$ and typically higher dispersion.

Reducing $\gamma$ obviously improves the performance.

Which is the merit of the dispersion itself? For details see [C].

4. Conclusions

**RECEIVER REQUIREMENTS**
- ADC speed: using only 1.25 SpS (35 GSa/s) does not cause a substantial penalty
- ADC resolution: 5 bits are enough
  - 6 bits is better for PM-16QAM
- Electrical bandwidth: 10 GHz are enough

**NON-LINEAR MITIGATION**
- Ready
  - Avoid in-line compensation
  - New fibers with high dispersion (and low non-linearity)
- To come
  - Digital approaches
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