EFFECTIVENESS OF DIGITAL BACK-PROPAGATION AND SYMBOL-RATE OPTIMIZATION IN COHERENT WDM OPTICAL SYSTEMS

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In long-haul system, maximum reach is limited by non-linear effects

Symbol Rate Optimization (SRO) has been shown to be effective in non-linearity mitigation
  - Recent experiments and theoretical analysis have demonstrated the potential advantage of Multi-Carrier (MC) systems

Digital Back Propagation (DBP) at receiver is another technique to mitigate non-linearity

These techniques are based on quite different mechanisms: How do they combine their effectiveness? Can they be synergistic?
OUTLINE

- Theoretical analysis
  - Application of the EGN-model to evaluate the effectiveness of SRO, DBP and of their joint use

- Experimental analysis
  - Application of DBP to a Multi-Carrier experiment

- Conclusions
The Enhanced GN-model allows for precise evaluation of Non-Linear Interference (NLI)

- Properly account NLI dependence on modulation format and symbol rate
  - A Symbol Rate Optimization (SRO) can be applied to minimize NLI
- Neither the GN-model nor advanced XPM models were able to demonstrate SRO

EGN-model also allows to evaluate ultimate limits of DBP
IDEAL DBP LIMITS

\[ G_{\text{NLI,DBP}} = G_{\text{NLI}} - G_{\text{NLI,SCI}} \]

\[ \text{OSNR}_{\text{NL}} = \frac{P_{\text{ch}}}{P_{\text{ASE}} + P_{\text{NLI,DBP}}} \]
### OPTIMUM SYMBOL RATE

- From EGN-model, we can derive an optimum $R_S$

$$R_{S, opt} = \sqrt{\frac{2}{\pi |\beta_2| N_{\text{span}} L_{\text{span}}}}$$

- Link parameters
  - SMF fiber
  - $L_{\text{span}} = 100$ km
  - $N_{\text{span}} = 50$

- Optimum symbol rate is too small for a practical implementation as a single carrier

- A multi-carrier solution is needed
  - Assuming an aggregate symbol rate $R_S = 32$ GBaud, we consider each channel split in 14 subcarriers
NLI MITIGATION: $G_{\text{NLI}}$ REDUCTION

$R_{S,\text{tot}} = 32$ GBaud
$
\rho = 0.05
$
$\Delta f = 33.6$ GHz
$N_{sc} = 14$
PM-QPSK
SMF
50 spans
$L_{\text{span}}=100$ km

NLI MITIGATION: SRO

SRO

1.80 dB

System Bandwidth [THz]

NLI mitigation [dB]
NLI MITIGATION: SRO & DBP

PM-QPSK
SMF
50 spans
$L_{\text{span}} = 100$ km

System Bandwidth [THz] vs. NLI mitigation [dB]

- SRO: 1.80 dB
- DBP: 1.23 dB
NLI MITIGATION: SRO & DBP

PM-QPSK
SMF
50 spans
$L_{\text{span}}=100$ km

![Graph showing NLI mitigation vs. system bandwidth.](image)

- **SRO**: 2.70 dB
- **DBP**: 1.80 dB
- **SRO & DBP**: 1.23 dB

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NLI MITIGATION: SRO & DBP

PM-16QAM
SMF
50 spans
$L_{\text{span}}=100$ km

<table>
<thead>
<tr>
<th>System Bandwidth [THz]</th>
<th>SRO</th>
<th>DBP</th>
<th>SRO &amp; DBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.01 dB</td>
<td>1.17 dB</td>
<td>1.05 dB</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
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</tr>
<tr>
<td>1</td>
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<td>3</td>
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<td>5</td>
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</tbody>
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How does NLI mitigation translate into Maximum Reach Gain?

Maximum Reach Gain [dB] = \( \frac{\text{NLI mitigation [dB]}}{3} \)

### PM-QPSK on C-band

<table>
<thead>
<tr>
<th></th>
<th>NLI Mitigation [dB]</th>
<th>MR Gain [dB]</th>
<th>MR Gain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRO</td>
<td>1.80</td>
<td>0.60</td>
<td>15%</td>
</tr>
<tr>
<td>DBP</td>
<td>1.23</td>
<td>0.41</td>
<td>10%</td>
</tr>
<tr>
<td>SRO &amp; DBP</td>
<td>2.70</td>
<td>0.90</td>
<td>23%</td>
</tr>
</tbody>
</table>

### PM-16QAM on C-band

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<th>MR Gain [dB]</th>
<th>MR Gain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRO</td>
<td>1.05</td>
<td>0.35</td>
<td>8%</td>
</tr>
<tr>
<td>DBP</td>
<td>1.17</td>
<td>0.38</td>
<td>9%</td>
</tr>
<tr>
<td>SRO &amp; DBP</td>
<td>2.01</td>
<td>0.67</td>
<td>17%</td>
</tr>
</tbody>
</table>
DN_MZM: double-nested Mach-Zehnder mod.

GEQ: Gain Equalizing programmable filter
PS: synchronous Polarization Scrambler
AOM: Acousto-Optic Modulator (used as switch)
TOF: Tunable Optical Filter

PSCF fiber kindly provided by

TRANSMISSION EXPERIMENT: SC VS. MC

- We started out with a **19 channel** WDM comb, with channel spacing **37.5 GHz**, for a total WDM bandwidth of **710 GHz**
- PM-QPSK channels with roll-off=0.05

- We then sent each channel as either:
  - single-carrier at **32 GBaund**
  - 8 subcarriers at **4 GBaund**
  - 16 subcarriers at **2 GBaund**

- Note that the spectral occupancy did not change: \( \Delta f_{SC} = 1.05 \cdot R_s \)
The 8x8 (real) LMS is necessary to correct for I/Q delay skew at the transmitter modulator (otherwise 4x4 is enough).
To perform a meaningful comparative test over the long-haul, it is important that the btb is the same.
MAXIMUM REACH AT BER=10^{-2}
MAXIMUM REACH AT BER=$10^{-2}$

Single carrier at 32 GBaud

- $12620 \text{ km}$
- $1x32G$

- Circle: experiment

\[ P_{TX} \text{ per subcarrier} [\text{dBm}] \]
Best-fit of EDFA noise-figure operated on the linear region: NF=5.2 dB
No further best-fit for ALL other EGN curves

$$\text{OSNR}_{NL} = \frac{P_{ch} - P_{NLI, signal}}{P_{ASE} + P_{NLI, signal} + ASE}$$

$$P_{TX} \text{ per subcarrier [dBm]}$$

Circle: experiment
Solid line: EGN

MAXIMUM REACH AT BER=10^{-2}

Multi-Carrier: 8x 4 GBAud and 16x2 GBAud

- Circle: experiment
- Solid line: EGN

- 12620 km
- 14180 km
- 14180 km (12.4%)
MAXIMUM REACH AT BER=10^{-2}

Multi-Carrier: 8x 4 GBaud and 16x2 GBaud

- Circle: experiment
- Solid line: EGN

14180 km
12620 km

12.4%
MAXIMUM REACH AT BER=10^{-2}

DBP with 5 steps per span

- 15040 km: 6.1%
- 14180 km: 0%
- 13792 km: 9.3%
- 12620 km: 0%

- Circle: experiment
- Solid line: EGN

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MAXIMUM REACH AT BER=10^{-2}

EGN predictions with DBP

\[ \text{OSNR}_{NL} = \frac{P_{ch} - P_{NLI,signal}}{P_{ASE} + P_{NLI,signal + ASE} - P_{NLI,SCI}} \]

- Circle: experiment
- Solid line: EGN
- Dashed line: EGN wDBP
MAXIMUM REACH AT BER=10^{-2}

EGN predictions with DBP and ASE corrections

OSNR_{NL} = \frac{P_{\text{ch}} - P_{\text{NLI,signal}}}{P_{\text{ASE}} + P_{\text{NLI,signal} + \text{ASE}} - P_{\text{NLI,SCI}} + P_{\text{NLI,ASE+DBP}}}

- Circle: experiment
- Solid line: EGN
- Dashed line: EGN wDBP
- Dash-dotted: EGN wDBP + ASEc

N_{\text{span}}

P_{\text{TX}} \text{ per subcarrier [dBm]}

16x2G, 8x4G, 1x32G

12.0 %, 13.5 %, 18.3 %
Theoretical analysis combining SRO and DBP shows that the two techniques are potentially synergistic.

Our ULH experiment confirm some advantages of combining SRO and DBP.

SRO deliver all the expected NLI mitigation.

DBP underperform its expected benefit:
- DBP is vulnerable when applied in low-OSNR conditions
- Polarization effects also hinder DBP effectiveness

In higher-OSNR systems, like PM-16QAM, DBP may result more effective.
ACKNOWLEDGMENTS

THANK YOU!

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