DIGITAL SIGNAL PROCESSING TECHNIQUES FOR HIGH-SPEED OPTICAL COMMUNICATIONS LINKS

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FINAL PHD DEFENSE

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STRUCTURE OF THE TALK

- **Part I: Direct-Detection Systems**
  - Bi-directional PAM-4 architecture for intra-data-center links
  - Self-coherent systems for data-center interconnections

- **Part II: Coherent Systems**
  - Probabilistic constellation shaping: basics over a pure AWGN channel
  - Interaction between PS and fiber non-linear effects: generation and compensation of non-linear phase noise
Part of the work presented here has been done in collaboration with CISCO Photonics Italy S.r.l. and LINKS Foundation
MOTIVATION: LINE RATES INCREASE

Peter J. Winzer, David T. Neilson, Andrew R. Chraplyvy, "Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]," Opt. Express 26, 24190-24239 (2018);
PART I

DIRECT-DETECTION SYSTEMS
Data Center Links

- **Within Data Center (71.5%)**
  - Storage, production and development data, authentication

- **Data Center to Data Center (13.6%)**
  - Replication, CDN, intercloud links

- **Data Center to User (14.9%)**
  - Web, email internal VoD, WebEx...

Total East-West traffic will be 85%
(Rack-local traffic would add another slice twice the size of "Within Data Center")

Source: Cisco Global Cloud Index, 2016-2021.
INTRA-DC CONNECTIONS

A “SPATIAL MULTIPLEXING” PROPOSAL
REQUIREMENTS FOR FUTURE INTRA-DC LINKS

- Speed
- Cost
- Size
- Power consumption
400GBASE-FR8 STANDARD

- 8 WDM channels, 800 GHz spacing
- 50 Gbit/s per channel
- Two transceivers, duplex SMF cable
  - How to reduce power consumption?
Lasers are shared inside each transceiver (like MPO)
- Duplex cable used simultaneously in both directions, like in PONs

**Double per-laser capacity**
- Unavoidable link-budget loss due to 3-dB splitters

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MAIN ISSUE: BACK-REFLECTIONS

- Back-reflections cause coherent crosstalk
- PONs use completely different wavelength (in O- and C-bands)
- Proposal: *slight* detuning, staying in the same WDM channel

GOAL OF THIS WORK

- **Back-reflection penalty** as a function of laser frequency separation for 2-km PAM-4 links

- Demonstrate that a *small* separation is sufficient to keep penalty *low* (<0.5 dB) for “standard” reflections
  - For instance, legacy TIA-568 LC connectors have a maximum back-reflection of -26 dB
EXPERIMENTAL SETUP

- 1550-nm transmission using DS fiber to emulate 1310-nm
- 53 GBaud or 28 GBaud PAM-4

RECEIVER STRUCTURE AND DSP

BER threshold: $2 \times 10^{-4}$ (KP4 FEC)

SINGLE REFLECTION RESULTS – 28 GBAUD

- Rule of thumb: $\Delta f > R_s$
- Feasible in the LAN-WDM grid (800-GHz spacing)

SINGLE REFLECTION RESULTS – 53 GBAUD

- Rule of thumb: 
  \[ \Delta f > R_s \]

MULTIPLE REFLECTIONS

Trans. “A”

\[ P_{\text{refl}} \propto \left| R_1 e^{j\phi_1} + R_2 e^{j\phi_2} + R_3 e^{j\phi_3} \right|^2 \]

Trans. “B”

THREE REFLECTIONS RESULTS – 28 GBAUD

- Multiple-reflection penalty is random
- Worst-case over 100 measurements
- **Rule of thumb**: $\Delta f > 2R_s$

$R$ is normalized to have the same reflected power at the receiver

A bi-directional architecture can potentially double per-laser capacity over standard duplex SMF cables

- There are still several issues to be solved: power budget due to 3-dB splitters, laser wavelength control, ...

- Back-reflection penalties can be avoided if lasers in one transceiver are slightly detuned
  - Rule of thumb: $\Delta f > 2R_s$
  - Keeps same nominal channel in WDM grid

INTER-DC CONNECTIONS

COHERENT OR DIRECT DETECTION?
WHICH MODULATION FORMAT FOR DCI?

Main characteristics for this scenario

- Standard single-mode fiber (SSMF) up to 100km
- C-band (EDFAs required at TX and RX)
  - Dispersion must be compensated
- High spectral efficiency not required
- Low cost and power consumption

Coherent or direct detection?

Inphi and Microsoft: PAM-4 (current), PM-16QAM (future)

SINGLE-SIDEBAND SELF-COHERENT TRANSMITTER

\[ |x(t) + c \cdot e^{-j2\pi t R_s/2}|^2 = |x(t)|^2 + c^2 + 2c \cdot \Re \left\{ x(t)e^{j2\pi t R_s/2} \right\} \]

Signal-Signal Beating Interference (SSBI) (can be compensated for)

SSB TRANSMISSION: PROS AND CONS

1. Direct detection ✓
2. Higher spectral efficiency ✓
3. Electronic dispersion compensation ✓

1. Complex transmitter structure ❌
2. High receiver analog bandwidth ❌
3. Reduced OSNR sensitivity ❌

DMT MODULATION: INTENSITY MODULATION OR SINGLE SIDE-BAND?
DISCRETE-MULTITONE MODULATION (DMT)

- Partial compensation of the frequency response of a dispersion-uncompensated IM/DD link

Source: T. Takahara et al., Proc. OFC 2014, M2I.1
## Simulation Setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT size</td>
<td>1024</td>
</tr>
<tr>
<td>Bitrate</td>
<td>120 Gbit/s</td>
</tr>
<tr>
<td>DAC sampling rate</td>
<td>64 GS/s</td>
</tr>
<tr>
<td>BER threshold</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>DAC 3-dB bandwidth</td>
<td>13 GHz</td>
</tr>
<tr>
<td>DAC resolution</td>
<td>6 bit</td>
</tr>
</tbody>
</table>

**Diagram:**

- **DMT TX DSP**
- **LASER**
- **Linear power mod**
- **DSB**
- **OBPF**
- **VSB**
- **SSB**

**Flowchart:**

- TX
- SMF
- VOA
- OBPF
- PD
- ADC
- RX

**Figure:**

TOLERANCE TO CHROMATIC DISPERSION

- SSB is practically unaffected by CD
- DSB/VSBS: strong OSNR penalty
- VSB filter: SuperGaussian

CONCLUSIONS ON INTRA-DC

- SSB self-coherent is a viable “hybrid” between direct detection and coherent
  - Advanced techniques like Kramers-Kronig are able to fully compensate for SSBI

- Excellent performance on ~80km dispersion-uncompensated links
  - IM/DD systems must use optical dispersion compensation, even with DMT and bit loading
  - Nevertheless, there are still several practical implementation issues that need to be solved
PART II

COHERENT SYSTEMS

AN INTRODUCTION
GENERIC COHERENT LONG-HAUL SYSTEM

- ASE noise
- Fiber Kerr effect
DSP point of view: equivalent channel

- Using theoretical models, simulations or experiments DSP can be tested, and performance metrics obtained
Mutual Information (MI)

Generalized Mutual Information (GMI)
Assuming Bit-Interleaved Coded Modulation (BICM)

Linked to the performance of soft-decision FEC codes
PROBABILISTIC CONSTELLATION SHAPING

BASICS OVER AN AWGN CHANNEL
STANDARD QAM CONSTELLATIONS

- ~1.53 dB asymptotic gap to capacity
- Fixed data rates!
  - Unless different FEC rates are used
The two goals can be achieved by transmitting QAM symbols with different probability.
1. How to implement constellation shaping?
   ▪ Implementable in hardware with low complexity
   ▪ Must be combined with Forward Error Correction

2. Which probability distribution?
   ▪ Potentially *any* distribution can be applied
   ▪ AWGN channel: optimal distribution is Gaussian (infinite number of points...)
- Practical, capacity achieving combination of shaping and coding
- Distribution matcher (DM): random stream of bits to sequence of amplitudes $A$ with desired distribution

NET (POST-FEC) DATA RATE

- Standard QAM constellations:
  \[ \text{AIR}_{\text{U}} = r_{\text{U}} m_{\text{U}} \]

  - FEC code rate
  - Constellation bit/symb.

- Probabilistic shaping with PAS scheme and ideal DM:
  \[ \text{AIR}_{\text{PS}} = H(P) - (1 - r)m \]

  - Entropy of PS constellation
  - FEC code rate
  - Constellation bit/symb.

MAXWELL-BOLTZMANN VS EXPONENTIAL

\[ P(a_i) \propto e^{-\lambda |a_i|^2} \]

AN EXPERIMENTAL COMPARISON

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Entropy (bit/symb)</th>
<th>FEC overhead</th>
<th>Distribution</th>
<th>Net data rate at 16 GBd</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-QAM</td>
<td>4</td>
<td></td>
<td>-</td>
<td>106.6 Gbit/s</td>
</tr>
<tr>
<td>PS-64-QAM</td>
<td>4.33</td>
<td>20%</td>
<td>Exponential</td>
<td>133.3 Gbit/s</td>
</tr>
<tr>
<td>32-QAM</td>
<td>5</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>PS-64-QAM</td>
<td>5.17</td>
<td></td>
<td>Exponential</td>
<td></td>
</tr>
</tbody>
</table>

4.33 bit/symb

5.17 bit/symb

EXPERIMENTAL SETUP

Parameter | Value
---|---
EDFA noise figure | 5.2 dB
Chromatic dispersion | 20.17 ps/(nm km)
Non-linearity coeff. | 0.75 1/(W km)
Attenuation | 0.16 dB/km

$R_s = 16$ GBd, $\Delta f = 25$ GHz

1. Ideal (i.e. genie-aided) phase noise removal (IPNR)
2. Blind Phase Search (BPS) + Maximum Likelihood (ML) with pilot tones for phase unwrapping

**OPTICAL BACK-TO-BACK RESULTS**

- **Solid lines**: AWGN (theory)
- **Markers**: Experimental measurements

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PSCF PROPAGATION RESULTS

- **Markers**: BPS+ML
- **Solid lines**: IPNR

After propagation over PSCF, PS-64-QAM keeps the same back-to-back sensitivity gain over 16-QAM and 32-QAM
  - Directly translated to a reach increase

In this scenario, Probabilistic Shaping does not change the impact of fiber Kerr non-linearities
PROBABILISTIC SHAPING AND FIBER NON-LINEARITIES

NON-LINEAR PHASE NOISE AND ITS IMPACT
\( h = 0 \) and \( k = m \) -> one of the largest contributor of the sum

\[ \Delta a_0 = 2j\gamma \sum_{h,k,m} a_h b_k^* b_m X_{h,k,m} \]

\( h = 0 \) and \( k = m \) -> one of the largest contributor of the sum

\[ \Delta a_{0p} = ja_0 \left( 2\gamma \sum |b_m|^2 X_{0,m,m} \right) \]

Phase noise component, with variance

\[ \Delta \theta^2 = 4\gamma^2 \left( \langle |b_0|^4 \rangle - \langle |b_0|^2 \rangle^2 \right) \sum_m X_{0,m,m}^2 \]
PROPERTIES OF NON-LINEAR PHASE NOISE

- Modulation format dependence:
  - Auto-correlation function of phase noise:
    - Simple approximation:

\[
\langle |b_0|^4 \rangle - \langle |b_0|^2 \rangle^2 = \begin{cases} 
0 & \text{QPSK} \\
0.32\sigma_b^4 & 16\text{-QAM} \\
0.381\sigma_b^4 & 64\text{-QAM} \\
\sigma_b^4 & \text{Gaussian}
\end{cases}
\]

\[
R_\theta(l) \approx \Delta \theta^2 \left[ 1 - \frac{|l|T}{|\beta_2\Omega|L} \right]^+
\]

Distance, dispersion and symbol rate enlarge the auto-correlation
Over PSCF we found no difference in NLI between the two constellations.

Non-linear phase noise (NLPN) is almost fully compensated for by the CPE.
EXAMPLE 1: LOW DISPERSION FIBER (NZDSF)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>NGMI th. = 0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromatic dispersion</td>
<td>2.65 ps/(nm km)</td>
<td></td>
</tr>
<tr>
<td>Non-linearity coeff.</td>
<td>2 1/(W km)</td>
<td></td>
</tr>
<tr>
<td>Attenuation</td>
<td>0.23 dB/km</td>
<td></td>
</tr>
</tbody>
</table>

EXAMPLE II: LOW SYMBOL RATE

15 x 32 Gbaud, 100-km SMF, simulations

As predicted by NLI models, PS constellations generate more non-linear phase noise

- If its memory (autocorrelation) is large (e.g. PSCF propagation), the CPE at the receiver is able to compensate for it

In some situations (e.g. low dispersion fibers, low symbol rates, ...) the CPE cannot fully compensate for NLPN

- Significant penalties can be expected
Several works were devoted to this topic

In this thesis are proposed two techniques:

1. Modified soft-decoding metric at the receiver
2. Geometrical constellation shaping
 Channel model:

\[ y[k] = a[k]e^{j\phi[k]} + n_{\text{ASE}}[k] + n_{\text{NLI}}[k] \]

Assuming memoryless phase noise, channel probability can be expressed as:

\[
p(y|a) \approx \sqrt{\frac{\kappa_\phi}{8\pi^3}} \frac{e^{-\kappa_\phi}}{\sigma_n^2} \exp \left( -\frac{|y|^2 + |a|^2}{2\sigma_n^2} + \frac{ya^*}{\sigma_n^2} + \kappa_\phi \right)
\]

Mitigation of residual (i.e. post-CPE) phase noise
- Experiment over low-dispersion fibers previously presented
- Significant reach gain on PS-64-QAM
- Smaller gain over standard QAM constellations
• Simulated annealing algorithm
  • Optimization metric: modified soft-decoding strategy
• A 32-point constellation (GS 32-QAM) was generated

• 31 x 16 GBaud, 80-km SMF, experiment
• All constellation have the same spectral efficiency
  ▪ NGMI threshold = 0.86
• No NLI penalty with GS 32-QAM
  ▪ PS 64-QAM is still better

Constellation shaping is a powerful technique to allow high data-rate flexibility.

However, it inevitably triggers more non-linear effects:
- Mostly, as non-linear phase noise.

In “standard” conditions (high dispersion, high symbol rates), receiver CPE compensates for it:
- At least for PS-64-QAM and reach ~hundreds of km.

Specific focus on NLPN mitigation must be taken into account in this cases:
- Or don’t use shaping 😊
LIST OF JOURNAL PUBLICATIONS

1. **Dario Pilori**, Antonino Nespola, Fabrizio Forghieri and Gabriella Bosco. “*Non-Linear Phase Noise Mitigation over Systems using Constellation Shaping*”. Submitted to: Journal of Lightwave Technology


LIST OF PRESENTATIONS


7. Dario Pilori, Mattia Cantono, Andrea Carena, and Vittorio Curri. “FFSS: The fast fiber simulator software”. International Conference on Transparent Optical Networks (ICTON), Girona (Spain), July 2017.


THANK YOU

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BACKUP SLIDES
SPEED OF INTRA-DC INTERFACES

ETHERNET SPEEDS

InfiniBand Roadmap

Link Bandwidth per direction, Gb/s

QDR 12x FDR 100G HDR 100G NDR 100G XDR 100G

Network Resources

10G 20G 40G 100G 200G 500G 1T

Quad Lanes
in QSFP

Serial Lane
in SFP

2005 2010 2015 2020 2025
8GFC 16GFC 32GFC 64GFC 128GFC 256GFC 512GFC 1TFC

InfiniBand Trade Association

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Fibre Channel Speed Speed in Development Future Speed PCIE Speed Speed in Development Possible Future Speed

OPTCOM
FORM FACTORS

1-4 Lane Interfaces

4-16 Lane Interfaces

Twisted Pair Cat "x"

Twine

Duplex and Parallel Optical Fiber

*Square inches of top surface of the module

Twisted Pair Cat "x"

Twine

Duplex and Parallel Optical Fiber

*Square inches of top surface of the module
**COHERENT OR DIRECT DETECTION?**

<table>
<thead>
<tr>
<th></th>
<th>PAM-4</th>
<th>16-QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(direct detection)</td>
<td></td>
<td>(coherent detection)</td>
</tr>
<tr>
<td><strong>Spectral efficiency</strong></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>TX architecture</strong></td>
<td>DAC</td>
<td>2xDAC</td>
</tr>
<tr>
<td></td>
<td>LASER</td>
<td>IQM</td>
</tr>
<tr>
<td></td>
<td>IM</td>
<td>2xDAC</td>
</tr>
<tr>
<td><strong>RX architecture</strong></td>
<td>PD</td>
<td>DP</td>
</tr>
<tr>
<td><strong>Dispersion compensation</strong></td>
<td>Optical</td>
<td>Electrical</td>
</tr>
</tbody>
</table>
PERFORMANCE COMPARISON: EXP VS MB

- Probability vs. $|\chi|$ graph
- MI vs. SNR (dB) graph

Options:
- Maxwell-Boltzmann
- Exponential
- Penalty is ~0.9 dB for standard QAM and ~1.05 dB for PS 64QAM
COMPARISON WITH NLI MODELS

16-QAM

PS-64-QAM 4.33-bit

32-QAM

PS-64-QAM 5.17-bit
64-APSK CONSTELLATION

![64-APSK Constellation Diagram](image)

![Graph showing gap to capacity vs SNR](image)
CHOICE OF SYMBOL RATE

- To carry out a fair comparison we kept fixed:
  - Total optical bandwidth
  - Relative channel spacing
  - Total bit rate is also constant

- Same laser phase noise: 2.5 kHz / GBaud

- The reference single-channel case is:
  - \( R_s = 32 \text{GBaud}, \Delta f = 50 \text{GHz}, \quad N_{\text{ch}} = 15 \text{ channels}, \quad \rho = 15\% \)

- We reduced symbol rate to 16, 8 and 4 GBaud