Scalable modulation technology and the tradeoff of reach, spectral efficiency, and complexity

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### Introduction

- **Huge bandwidth and capacity demand increase**
  - driven by video streaming, cloud computing, social media and mobile applications

- **Need to increase the transmission rate of currently deployed systems**
  - 32-Gbaud PM-QPSK $\rightarrow$ 128 Gb/s per channel
  - 32-Gbaud PM-16QAM $\rightarrow$ 256 Gb/s per channel

### Global IP Traffic by Devices

*Source: “The Zettabyte Era - Trends and Analysis”, Cisco, Jun 2016*

Raw bit-rate

$$R_b = R_s \cdot n_{bps}$$

- **Symbol rate**
- **Number of bits per symbol**

*25% CAGR 2015–2020*
Goal: to scale the per-channel bit rate to 400 Gb/s and beyond

Two options:
- Increase $n_{bps}$ → high-order formats → Trade-off between spectral efficiency and reach
- Increase $R_s$ → Impact of symbol-rate on system reach

Raw bit-rate

$$R_b = R_s \cdot n_{bps}$$

Net bit-rate

$$R_b = R_s \cdot n_{bps} \cdot r$$

FEC with 20% over-head ($r = 0.833$)
Outline

- Introduction
- Nyquist-WDM
- Trade-offs between spectral efficiency and reach
- Impact of symbol-rate on system reach
- Subcarrier multiplexing
- Probabilistic shaping
- Conclusions
Introduction

Nyquist-WDM

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Nyquist-WDM

- Maximum information that can be transmitted by the WDM comb: SE x available bandwidth

![Diagram of Nyquist-WDM](image)

**Raw spectral efficiency**

\[ SE = n_{bps} \cdot \frac{R_s}{\Delta f} \]
Generation of a Nyquist-WDM signal

- $R_s = \frac{f_{DAC}}{N_{SpS}}$
  - DAC sampling speed (samp/s)
  - Number of samples per symbol

- $R_s$ can be increased by reducing the “oversampling factor” $N_{SpS}$ → interference between spectral replica → need to use a proper anti-alias filter

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A. Nespola et al., “1306-km 20x124.8-Gb/s PM-64QAM Transmission over PSCF with Net SEDP 11,300 (b·km)/s/Hz using 1.15 samp/symb DAC,” *Opt. Exp.* (22), 2014.
Nyquist pulse shaping is performed in the digital domain using FIR filters with a roll-off of 0.1.
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Trade-off between complexity and achievable spectral efficiency.
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Trade-offs between spectral efficiency and reach

Net spectral efficiency

\[ SE = n_{\text{bps}} \cdot \frac{R_s}{\Delta f} \cdot r \]

- If \( n_{\text{bps}} \) increases, SE increases but the back-to-back performance gets worse \( \rightarrow \) reduction in reach

Analysed setup:
- Nyquist-WDM transmission at \( R_s = 32 \) Gbaud, with spacing \( \Delta f = 1.05 \) \( R_s \) (roll-off 0.05)
- Bandwidth of the WDM comb: 5 THz
- EDFA only amplification with \( F = 5 \) dB
- PSCF or SSMF with 100-km span length
- SNR margin of 3 dB w.r.t. the ideal back-to-back performance
SE vs. total link length (100-km span length)

<table>
<thead>
<tr>
<th>Link</th>
<th>Fiber type</th>
<th>Dispersion [ps/nm/km]</th>
<th>Loss [dB/km]</th>
<th>Non-linearity coeff. [W^{-1}km^{-1}]</th>
<th>Span length [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link 1</td>
<td>SSMF</td>
<td>16.7</td>
<td>0.2</td>
<td>1.3</td>
<td>100</td>
</tr>
<tr>
<td>Link 2</td>
<td>PSCF</td>
<td>20.5</td>
<td>0.165</td>
<td>0.75</td>
<td>100</td>
</tr>
</tbody>
</table>


- Distance between operating point and asymptotic performance → FEC overhead
- Complexity increases with modulation format order and FEC overhead
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Over the last few years, various simulative and theoretical papers have presented evidence of a **dependence of system performance on the transmission symbol rate**:

- C. Behrens et al., ‘Nonlinear transmission performance of higher-order modulation formats,’ PTL (23), Mar. 2011.
- M. Qiu et al., “Subcarrier multiplexing using DACs for fiber nonlinearity mitigation in coherent optical communication systems,” OFC 2014, paper Tu3J.2.
- N. Rossi, P. Serena, A. Bononi, ‘Symbol-rate dependence of dominant nonlinearity and reach in coherent WDM links, JLT (33), Jul. 2015.

**What is the symbol rate which minimizes the non-linear interference (NLI) ?**
The analyzed set-up

- **What is the symbol rate which minimizes NLI?**
  
  ...having fixed:
  - the total WDM bandwidth \( B_{\text{WDM}} = 504 \text{ GHz}, 1.5 \text{ THz}, 2.5 \text{ THz}, 5 \text{ THz} \)
  - the modulation format and roll-off (PM-QPSK, \( \rho = 0.05 \))
  - the relative frequency spacing \( \Delta f = 1.05 R_s \)
  
- SSMF fiber (100-km span length)
  - EDFA-only amplification (\( F = 5 \text{ dB} \))
The total NLI power ($P_{\text{NLI}}$) at the output of the transmission link is estimated either with the EGN model [*] or by numerical simulations based on the split-step Fourier method.

Systems at different symbol rate are compared in terms of the normalized NLI power spectral density (PSD)

$$\tilde{G}_{\text{NLI}} = \frac{P_{\text{NLI}}}{R_s G_{\text{ch}}^3}$$

which is independent of the transmitted power per channel.

Same value of $\tilde{G}_{\text{NLI}}$ means same maximum reach.

Normalized $G_{\text{NL}}$ – PM-QPSK over SMF

- Solid lines: EGN model

Solid lines: EGN model
Markers: numerical simulations

Maximum reach gain:

\[ (\Delta MR)_{dB} \approx \frac{1}{3}(\Delta \tilde{G}_{NLi})_{dB} \]

\~ 0.6 dB or 15%

How to exploit symbol-rate optimization gain?

- Optimum symbol rate values in the range 2-4 Gbaud
- It would be extremely inefficient to use a separate transceiver for each low-symbol-rate signal
  - To reach the transmission speed of commercially available 32-Gbaud systems, 16× more transceivers (including laser sources) at 2 Gbaud would be required

**Sub-carrier multiplexing**

- A high symbol-rate signal is electrically decomposed into a given number of subcarriers, each of which operating at a lower symbol-rate (multiplexing in the digital domain)
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Subcarrier multiplexing

The experiment

- We started out with a **19 channel** WDM comb, with channel **spacing 37.5 GHz**, for a total WDM bandwidth of **710 GHz**

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

  **Note that the spectral occupancy did not change**
• The 8-subcarrier DAC-generated *electrical* spectrum for one channel
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
The Rx DSP

- 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.

At the reference BER=10^-2:
- No penalty from single SC to 8 SCs
- 0.1-dB penalty from single SC to 16 SCs
Reach curves at BER $10^{-2}$

- **16 subcarriers**
- **8 subcarriers**

14180 km

12620 km

12.4 % reach increase

- markers: experiment
- solid lines: EGN model predictions

Launched Power per subcarrier [dBm]

Number of spans
Pros and cons of SCM transmission

PROS

- Exploitation of the nonlinear propagation benefits associated with SRO (symbol rate optimization)
- Increase of system flexibility, by adjusting the number of subcarriers, modulation formats and spectral occupation to the current load of the network.

CONS

- Higher sensitivity to transceiver impairments (like IQ-skew) and phase noise → requires more complex DSP algorithms
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- Shaping reduces the maximum achievable mutual information (or, equivalently, transmit rate), represented by the MI floor for high values of SNR.

- This value corresponds to the constellation entropy:

\[ H(C) = - \sum_i p(a_i) \log_2 p(a_i) \]

- For low values of SNR, PS constellations perform slightly better than uniform 64-QAM.
- PS-64QAM with the same entropy as the uniform 16-QAM constellation
- PSCF fiber (108-km span length)
- 11 WDM channels at 32 Gbaud (frequency spacing = 50 GHz)
- The maximum reach gain at the same mutual information is 13.75%, which corresponds approximately to the SNR gain in back-to-back.
Pros & Cons

**PROS**
- Enhanced system reach
- High flexibility of the transponder (transmission speed can be tuned by changing the shaping of the constellation)

**CONS**
- The highest SNR gains of probabilistic shaping are achieved for low values of MI, which corresponds to very high pre-FEC Symbol Error Rates (SERs)
- High values of SER represent a big challenge for blind DSP algorithms, such as adaptive equalizer and phase recovery.

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Two main strategies to increase the transmission speed:
- Increase the order of the modulation format
  → SNR penalty, increase of DSP complexity
- Increase the symbol rate

There is an optimum value of symbol-rate that minimizes the impact of nonlinearities (around 2-4 Gbaud) → subcarrier modulation
- more impacted by transceiver impairments (like IQ-skew) and phase noise
- requires more complex DSP algorithms
- increases flexibility

Other ways to increase flexibility
- Constellation shaping
- Hybrid formats