Signal Processing Techniques that Impact Optical Communications

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Thank You!!

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... and my excellent students and collaborators.
Outline

- Coherent detection and DSP
- DSP compensation of data degrading effects
  - dispersive and polarization effects.
- OSP in optical networks
Digital and Analog Signals

Digital Signals
- Laser → MZI → 0 1 1 0 1 0
- Generally, require high device linearity and prone to noise
- Appropriate for waveform manipulation (AWG)
- Microwave photonics
- Beam steering
- Military applications
- Radio over fiber
- A/D and D/A

Analog Signals
- Laser → MZI
- Generally, require lower signal-to-noise ratio (SNR)
- High data capacity
- Appropriate for coding and error correction
- Common in communications and signal processing

We will primarily discuss optical signal processing of digital signals.
Digital Modulation Formats

Optical wave: \( E = A \cos(2\pi ft + \varphi) \)

### Amplitude Modulation
- Information encoded on the amplitude of an optical wave
- On-off keying (OOK)
- Pulse amplitude modulation (PAM)

![OOK](OOK_image.png)

### Phase Modulation
- Information encoded on the phase of an optical wave
- Phase shift keying (PSK)
- \( n \) bits can create \( 2^n \) phase levels
  - BPSK: binary PSK
  - QPSK: quadrature PSK

![BPSK](BPSK_image.png)

### Amplitude and Phase Modulation
- Information encoded on both the amplitude and the phase
- Quadrature amplitude modulation (QAM)
- \( n \) bits can create \( 2^n \) phase/amplitude symbols, e.g., 16-QAM for \( n = 4 \).
The transmitter consists of two parallel PSK modulators that are integrated together in order to achieve phase stability.

Coherent receiver is used to recover the data on channel I and channel Q.
Coherent Detection

\[ E_S(t) = E_S(t) e^{j(\omega_S t + \phi_S(t))} \]

During Coherent Detection, the received signal is compared with a locally generated optical field \( E_{LO} \). The mixed signal is then sampled at the instant that the phases of the local and received fields are matched, which is typically done by using a 90° Hybrid. The mixed signal can be described as:

\[ |E_S(t) + E_{LO}|^2 = |E_S(t)|^2 + |E_{LO}|^2 + E_S(t) E_{LO} \cos(\omega_S t + \phi_S(t) - \omega_{LO} t + \phi_{LO}) \]

All linear distortions (chromatic dispersion, PMD, PDL) can theoretically be fully compensated.
Quadrature Amplitude Modulation (QAM)

<table>
<thead>
<tr>
<th>QAM Type</th>
<th>Spectral Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-QAM</td>
<td>4 bits/s/Hz</td>
</tr>
<tr>
<td>32-QAM</td>
<td>5 bits/s/Hz</td>
</tr>
<tr>
<td>64-QAM</td>
<td>6 bits/s/Hz</td>
</tr>
</tbody>
</table>

**QAM Generation**

H_t(f) \times \text{DATA} \rightarrow\rightarrow H_t(f) \times \cos2\pi f_0 t - \sin2\pi f_0 t

**Transmitted Signal**

H_r(f) \times \cos2\pi f_0 t - \sin2\pi f_0 t

**QAM Detection**

H_r(f) \times H_t(f) \rightarrow\rightarrow H_r(f) \times H_t(f)
Digital Coherent Receiver: Signal Processing

Optical input:

→

Clock recovery:
digital filtering and square timing recovery

→

Equalization:
4 complex FIR filter banks, optimized with LMS

→

Carrier recovery:
Viterbi-and-Viterbi 4th power phase estimation

→

Error counting:
differential decoding

C. Fludger, JLT, 2008
Digital Signal Processing in Coherent System

DSP at Receiver

- Analog to digital conversion
- Static & adaptive channel equalization
- Frequency offset estimation
- Carrier phase recovery

• DSP is effective to compensate for the impairment and distortion in the optical coherent system.

Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM is a multicarrier transmission technique where a data stream is carried with many lower-rate subcarrier (SC) tones. Subcarriers overlap in frequency domain.

- OFDM is demodulated to its constituent subcarriers using discrete Fourier transform (DFT).
Optical OFDM Multiplexing

Generating OFDM Signal from Subcarriers

- Each subcarrier data is modulated on one laser of an equidistance multi-wavelength source.
- Can achieve high baud rate on subcarriers and Tbit/s OFDM generation.

\[
s(t) = \sum_{n=0}^{N-1} x_n(t) e^{j2\pi(f_0 + n\Delta f)t}
\]
MZI-Based vs. OTDL-Based DFT

**MZI-Based Fast Fourier Transform**

- Each stage demultiplex a set of subcarriers
- Similar to FFT with conventional electronics


- Enable high capacity OFDM transmission
- Reconfigurable OFDM demultiplexing using DFT

**OTDL-Based Discrete Fourier Transform**

- Variable baud rate OFDM demultiplexing and signal processing.
- All subcarriers are demultiplexed simultaneously at the second stage.
- Like DFT in digital signal processing.

*M. Chitgarha, OL 2012*
All-optical Fast Fourier Transform (FFT)

- Optical FFT scheme to encode lower-bit-rate tributaries into 10.8- and 26.0-Tbit/s line rate OFDM signal

- 10.8 Tbit/s achieved using Nyquist rate, 25 Gbaud, 75 subcarriers, 16-QAM on the subcarriers and 28% cyclic prefix

Discrete Fourier Transform (DFT)

OTDL-Based Discrete Fourier Transform

- Reconfigurable all-optical DFT can be realized using frequency combs to multiplex and demultiplex OFDM subcarriers.
- Baud rate is tuned by tuning the delays (i.e., laser wavelengths).

\[ X[k] = \sum_{n=0}^{N-1} x[n]e^{\frac{j2\pi kn}{N}} \]

Demultiplexing of OFDM: Four 40-Gbaud QPSK Sub-channels

Nyquist Pulse Generation

Flat line insertion of coherent into a Kerr frequency comb

Kerr comb

CW WDM Channels

Nyquist WDM Channels

Denser frequency comb

No spectral band-guard and no ISI

Coherent and equalized line insertion into Kerr comb

Minimum bandwidth occupation due to sinc shape

Nyquist shape line insertion
Concept of flat-line insertion

Goals:
- Insertion of uniform set of strictly phase/frequency-locked lines around each Kerr comb line.
- Tunable in terms of number of the inserted lines and their frequency separation.
- Generation of coherent sinc-shaped Nyquist pulses of different widths and repetition rates.

F. Alishahi et al., OL, 2019.
Spectrum of 9 Nyquist Sinc-shaped Channels

- Kerr comb with FSR~ 192GHz
- Modulating frequencies; f1=18GHz and f2 =6GHz

Nyquist line insertion

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE(%)</td>
<td>6.1</td>
<td>6.0</td>
<td>5.5</td>
<td>5.0</td>
<td>4.5</td>
<td>4.3</td>
<td>4.2</td>
<td>4.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The deviation with theory for each channel

RMSE: Root-Mean-Square Error  
F. Alishahi et al., OL, 2019.
Outline

- Coherent detection and DSP
- DSP compensation of data degrading effects
  - dispersive and polarization effects.
- OSP in optical networks
Digital Signal Processing in Coherent System

Frequency offset estimation

- $f_{Tx}$ and $f_{Rx}$ may not be the same, need to estimate $f_\Delta = f_{Tx} - f_{Rx}$

Carrier phase recovery
**Coherent Reception-Enabled Compensation**

**Basic concept** – Linear distortions can be compensated quasi-exactly using finite impulse response filters. Some nonlinear distortions can only be compensated partially.

**Easy**

**Linear Impairments**
- Dispersion-related: CD, Dispersion Slope
- Polarization-related: PMD, PDL, Pol. Rotation
- ROADM and MUX / DEMUX filtering
- Higher-order CD and PMD

**Nonlinear Impairments**
- Self phase modulation; Cross phase modulation
- Four-wave mixing
- Nonlinear scattering (SBS, SRS, Rayleigh...)

**Hard**

**Amplified Spontaneous Noise**
- Amplified spontaneous emission noise
- ASE coupled with Kerr nonlinearities (nonlinear phase noise)

*E. Ip, OE, 2008*
Digital Signal Processing in Coherent System

Analog to digital conversion

Transmission through channel

Channel equalization

Input signal

Distorted signal

Recovered signal
Nonlinearity Mitigation via Coherent Detection

Amplified Spontaneous Emission
Signal Amplitude
Other Signals (WDM)

\[ n = n_0 + n_2 I(t) \]

Nonlinear phase noise

1000 km transmission of 20 Gbit/s QPSK waveform

Digital Backward Propagation (DBP)

Compensation of fiber nonlinearities

\[ E(0,t) \xrightarrow{\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix}} e^{\Delta z_1 (D^{(1)}_c + N^{(1)}_c)} \xrightarrow{\ldots} e^{\Delta z_{N_{sec}} (D^{(N_{sec})}_c + N^{(N_{sec})}_c)} \xrightarrow{\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}} E(L,t) \]

Outline

- Coherent detection and DSP
- DSP compensation of data degrading effects
  - dispersive and polarization effects.
- OSP in optical networks
What is optical signal processing (OSP)?

Examples of simple OSP functions

A lens can perform Fourier transform

K. von Bieren, AO, 1971

High BW pass-through
EDFA

What is OSP?

Potential advantages:

- Avoid O-E-O conversion
- Multiple dimensions (amplitude, phase, time, wavelength, polarization)
- Processing at line rate

Input

O/E

Electrical signal processing

E/O

Output

Optical signal processing

Photonic-assisted signal processing

“Large data” Tbit/s

Optical pattern recognition

Correlation peaks

Peak level

Symbol

Example: optical correlator

Gbit/s

Electrical pattern recognition

Mbit/s

User interface

M. R. Chitgarha, Optics Letters, 2014

Example: optical correlator

Gbit/s

Electrical pattern recognition

Mbit/s

User interface

M. R. Chitgarha, Optics Letters, 2014
Optical signal processing functions

Wavelength conversion

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>λ</th>
<th>Nonlinear element</th>
<th>Converted Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW Pump</td>
<td>λ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- simple and useful, but deployable?

Multicasting

<table>
<thead>
<tr>
<th>Input signal (lasers/comb)</th>
<th>Pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear element</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Multicast signals
  - Input signal
  - S₀
  - S₁
  - S₂
  - S₃

Example of frequency combs

On-chip Kerr frequency combs

- Coherent lines can be efficiently mixed.
- Could span >200-THz bandwidth.

Multicasting with comb lines

- Comb lines can be used instead of lasers.
- Coherent comb lines automatically cancel out the phase noise from pumps.

Kippenberg, Gaeta, Lipson, Gorodetsky, Science, 2018

P. Liao, Optics Letters, 2017
Phase Sensitive Amplifier for Optical Regeneration

Phase Insensitive Amplifier (EDFA)

\[ \phi_{\text{in}} \rightarrow \phi_{\text{out}} \]

Input

Output

Re (In Phase)

Im (Quadrature)

Degenerate FWM Phase Sensitive Amplifier

Pump 2

Pump 1

\[ \phi_{P2} \quad \phi_{S} \quad \phi_{P1} \]

Signal

FWM

Generated Signal (=idler)

\[ \phi_{\text{idler}} = \phi_{P2} + \phi_{P1} - \phi_{S} \]


Phase Sensitive Amplifier (PSA)

\[ \phi_{\text{in}} \rightarrow \phi_{\text{out}} \]

Input

Output

Re (In Phase)

Im (Quadrature)

Signal interferes with idler:

Constructively if:

\[ \phi_{S} = -\phi_{\text{idler}} + \pi \]

Amplification

Attenuation

Destructively if:

\[ \phi_{S} = -\phi_{\text{idler}} - \pi \]
Materials and Devices for High Nonlinearity

**Desired parameters**
- Wide and flat bandwidth
- Low loss
- High nonlinear efficiency
- Low dispersion for phase matching

**Linear Devices**
- Silicon microring resonator
- Mach-Zehnder interferometer

**Nonlinear Devices**
- Highly Nonlinear Fiber (HNLF)
- Periodically-Poled Lithium Niobate (PPLN) Waveguides
- SOA (Early work)
- ENZ (Early work)

*References*
Nonlinear Wave Mixing: Mutually Coherent Lines

### Degenerate FWM in $\chi^{(3)}$

- **FWM:** $f_{\text{conv}} = 2f_{\text{pump}} - f_{\text{sig}}$
  - Converted signal is phase conjugated
  - Limit on proximity to signal
  - Maximum efficiency when pump is near zero-dispersion wavelength (ZDW)

### Cascaded SFG and DFG in $\chi^{(2)}$

- **SFG:** Sum frequency generation, $f_{\text{SFG}} = f_{\text{signal}} + f_{\text{pump}}$
- **DFG:** Difference frequency generation, $f_{\text{converted}} = f_{\text{SFG}} - f_{\text{dummy}}$

**Wavelength converted copy:**

- $E_{\text{idler}} \sim E_{\text{signal}} \times E_{\text{pump}} \times E^*_{\text{dummy}}$
- $\phi_{\text{idler}} \sim \phi_{\text{signal}} + \phi_{\text{pump}} - \phi_{\text{dummy}}$

**HNLF (Silica)**

**PPLN waveguide (Lithium niobate)**

**QPM:** Quasi-phase matching
Implementations of optical tapped delay lines (TDL)

Concept of TDL

\[ y(t) = \sum_{k=1}^{N} a_k e^{i\phi_k} x(t - T_k) \]

- \( N \): number of taps
- \( a_k \): tap coefficients
- \( T_k \): tap delays
- \( \phi_k \): tap phases

\[ y(t) = a_1 e^{i\phi_1} x(t - T_1) + a_2 e^{i\phi_2} x(t - T_2) + \cdots + a_N e^{i\phi_N} x(t - T_N) \]

Input x(t) → Delay \( T_1 \) → Output y(t)

Linear devices

- Using MZI structures
- One element for each tap

Nonlinear devices

- Using wave mixing in nonlinear devices
- Single element mixing for multiple taps

Optical multicasting (nonlinear device)

- Input signal
- Signal copies

Optical multiplexing (nonlinear device)

- Output signal
- Signal copies

Y. Xie, Nanophotonics, 2018

Motivations for Flexible Networks

- Efficient use of resources
- Handle changes in users’ demand and quality of service
- Easier deployment of new services
- Enable heterogeneous channels

Cellular Network

SONET/SDH

Long-Haul Network

QPSK: Quadrature Phase Shift Keying
QAM: Quadrature Amplitude Modulation
PON: Passive Optical Networks
SONET: Synchronous Optical NETworking
PAM: Pulse Amplitude Modulation

EPON/GPON

PAM4

Data Center
OSP for Flexible Network in Physical Layer

Flexible Frequency Grid

Fixed ITU grid → \( \lambda \) → Flexible grid

Aggregation and De-aggregation

QPSK + 16-QAM = PAM-4

Dynamic Bandwidth Allocation

Input signals → Processed signals

Flexibility in Working Across Optical Band

Broad band technologies

E-Band, S-Band, C-Band, L-Band → \( \lambda \)
"Straight-forward" dynamic BW allocation can use wavelength conversion.

Data Center

Heterogeneous Bandwidth and Pulse Shaping

Increasing Spectral Efficiency by Overlapping Channels
Optical Modulation Format Conversion

- Combine channels from different parts of network into shared spectrum
Reconfigurable, High-Capacity Optical Transmitters

Optical-Time-Division-Multiplexing (OTDM)
- Bit-interleaving a large number of tributaries generates OTDM signal.
- OTDM signals can potentially be used at >1Tbit/s.

Quadrature-Amplitude-Modulations (QAM)
- Higher-order QAM can increase spectral efficiency.
- Multiple lower-order QAMs can be multiplexed into a higher-order QAM.

Orthogonal-Frequency-Division-Multiplexing (OFDM)
- OFDM provides high spectral efficiency compared with conventional subcarrier multiplexing.
- Mux/demux of OFDM subcarriers at very high line-rate.

Tributary #1

Subcarrier #1

Subcarrier #2

Subcarrier #N
**Goal:** Can an optical TDL operate on multiple-wavelength channels with independent functionality on individual channels?

**Approach:** Each tap is generated by two cascaded wavelength conjugative stages.

**Impact:** Efficient, reconfigurable, and independent processing of multiple signals to increase processing capacity.

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Independent Functions on Each Channel:
- Equalization
- Pattern Recognition (Correlation)
- Format Conversion

Multi-channel signal processing

Multi-channel De-Aggregation

- Coherent Pump $S_1 P_{12}$ $P_1$
- $P_{21}$ $S_2 P_{22}$

Wave mixing

- 16-QAM
- two PAM-4

Channel 1
- $S_1$ $S_1^*$
- $S_2$ $S_2^*$

Channel 2
- $P_1$
- $P_{12}$

Optical de-aggregations in one nonlinear device


WDM Wavelength conversion

- 1.55-um band: I/Q modulation
- pump: 1.74 um

2-um band signal generation

- 1.55-um band: coherent detection
- pump: 1.74 um

Operating the band.

Multi-channel signal processing

WDM phase regenerator

- Phase regeneration of 16-WDM channels in one PSA using time lenses
- Time lens-based OFT: combine WDM into a single serial channel

Flexible Transmitter and Bandwidth Allocation

Reconfigurable multiplexing results optimal use of high-speed terminal equipment.

- First, generating optical signal, then, reconfigurable multiplexing using OSP to create various outputs.

Flexible Optical QAM Transmitter

Output fiber with multiple wavelength channels

- Configuration #1: 64-QAM
- Configuration #2: QPSK 16-QAM
- Configuration #3: QPSK QPSK QPSK

Example: e.g., QPSK Signals
Flexible Transmitter

**Amplitude Weights:** [1, 0.5, 0.25]

- **CW Lasers**
- **QPSK Modulation**
- **Nonlinear Device (Phase Coherent Addition)**
- **BPSK or QPSK Modulated**
- **CW Lasers**

**Examples:**

- **1st BPSK**
- **2nd BPSK**
- **4 QAM**

- **1st QPSK**
- **2nd QPSK**
- **3rd QPSK**

- **1st QPSK = 45°**
- **2nd QPSK = 135°**
- **3rd QPSK = 225°**

- **64-QAM**

- **QAM S1 S2 S3 D3 D2 D1 P**

- **e.g., 64-QAM**

**Flexible Bandwidth Allocation using Wave Mixing**

**M. R. Chitgarha, OL, 2014.**
**All-optical de-aggregation**

**Motivation**
- Enable a transparent gateways between different communication networks
- Useful when the signals in long-haul are directed to access

**De-aggregation of 21.5 Gbit/s QPSK Signal in HNLF**

- MLL-based Comb
- WSS
- QPSK Modulator
- FS
- PLL
- HNLF
- Receiver

- TX-QPSK (Q)
- RX-BPSK (I)
- RX-BPSK (Q)

- Phase de-multiplexing of QPSK signal to BPSK signals
- OSNR penalty less than 1 dB compared to the B2B BPSK signal

*M. Gao, ECOC, 2013.*
Dynamic Subcarrier Allocation

- Variable bandwidth transmission by elastically controlling the number of subcarriers (multi-carrier modulation)
- Allocating subcarriers/slots for signals from different paths

Fragmented Bandwidth Allocation

System with two random slots

Copy generation by multicasting
Filtering each slot

B2B System with two random slots

Fragmented Bandwidth Allocation

Inserted Channel Slices

Copy generation by multicasting
Filtering each slot

Y. Cao, JLT, 2018.
Spectral Efficiency with Overlapped Channels

**Channel overlapping**

- Decrease the channel spacing to have spectral overlapped channels
- More channels can be allocated within the same total bandwidth.

**Problem**

Inter-channel Interference (ICI)

\[ S_{1_{ICI}} \approx S_1 + aS_2 \]
MIMO-Based Crosstalk Compensation

- Electrical ICI compensation based on MIMO algorithm
- Requires:
  - Recover all channels
  - Synchronization.

Two overlapped 128-Gb/s PDM-QPSK channels, channel spacing=25 GHz

Optical Mitigation of ICI for Multiple Overlapped Channels

Incoming optical overlapped channels

\[ S_1, S_2, S_3, S_4, S_5, S_6, S_7 \]

Conjugate copy generation (PPLN-1)

Programmable optical amplitude and phase filter (LCoS filter)

WDM \( \lambda \)-conversion in PPLN-2a (Even channels)

Optical filter

WDM \( \lambda \)-conversion in PPLN-2b (Odd channels)

Optical filter

Reduced ICI

Port-1

Port-2

Baudrate = 20 Gbaud

Channel spacing = 17.5 GHz

Optical ICI compensation at port 1 (even channels):

SHG + DFG Mixing
One example of most spectrally efficient DCIs:

- leveraging DSP (supercorner with multiple subcarriers) and advancements in photonic integration
- possibility of tuning the spectral occupancy of each signal by adjusting the baudrate of the modem

S. Grubb et al., OFC 2019.

### MAREA hero results over 6,640 km:
- Total capacity: 30 Tb/s on single fiber pair
- 700 Gb/s data rate per λ
Innovations in optical signal processing

Innovations that might enable the deployment of OSP:

- Photonic integrated processing
- Improved efficiency
- Processor composed of an array of MZIs
- Programmable photonic circuit
- Allow self-configuration


Photonic integrated processing

Concept

Fabrication

Control lines

Input/Output
Circuit Options

Digital Memory
(volatile, RAM)

Programmable
Analog Memory
Cell (non-volatile)

Phase-Change
Material (PCM)

Digital core

DAC

ADC

Driver ASIC

Neuromorphic photonics processor

Advancements in signal processing have been instrumental in the development of coherent optical communication systems, from long haul to data center applications.