High-spectral-efficiency optical modulation formats

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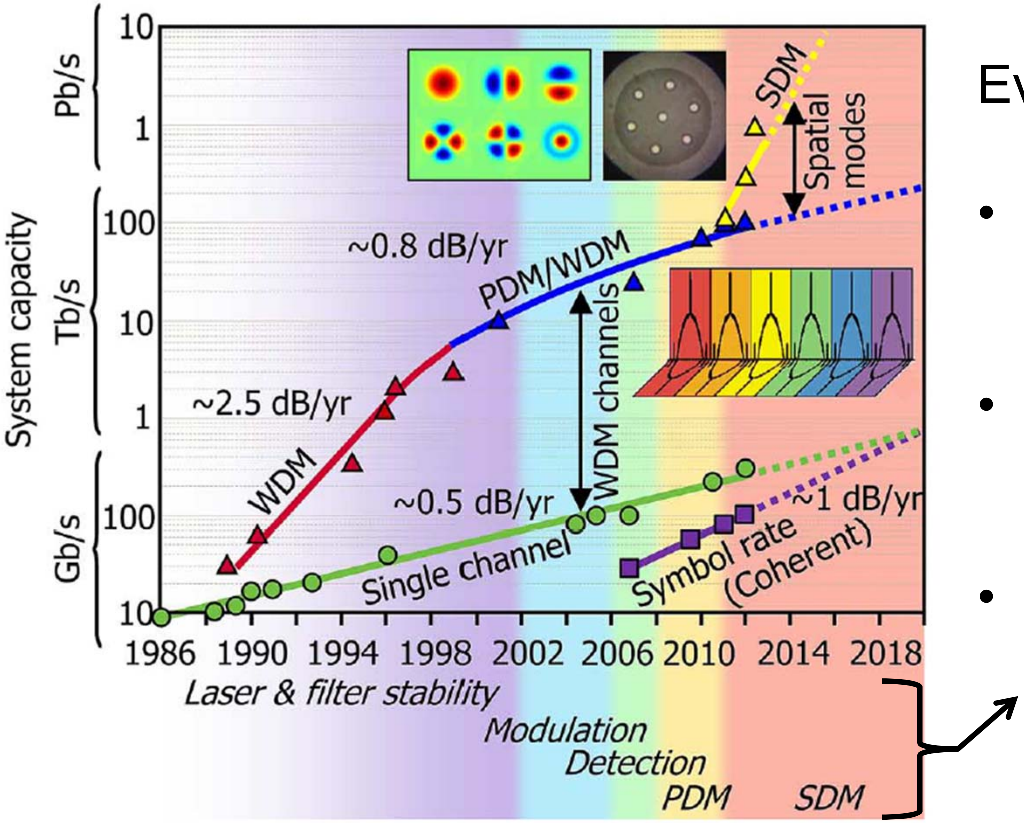
Contents

Introduction

- Communication system: grows exponentially
- Demand for communication bandwidth
  : wavelength-division multiplexed (WDM) optical transmission systems
- Researched, developed since the early 1990s
- Research experiments → commercial products follows in 5 years

Growth of optical communication system

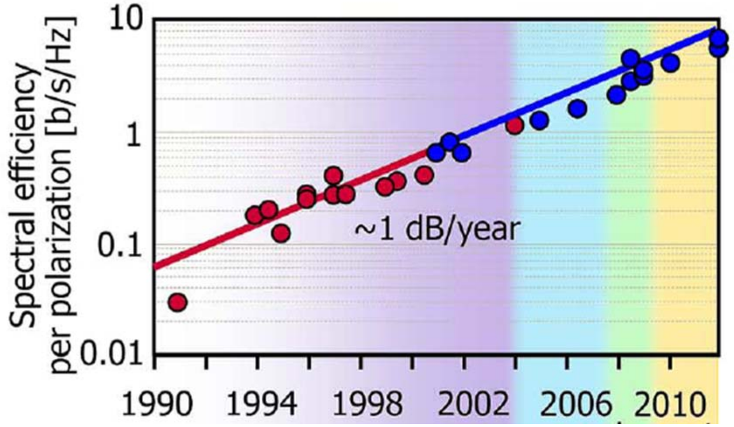


Evolution of various bit rates

- Single-channel bit rates
  : 0.5 dB/year
- Aggregate per-fiber capacities
  : 2.5 dB/year
- Rapid advances in optoelectronic device technologies

“Optical and electronic bandwidths had met”

- Advance in optical & electronic & optoelectronic device technologies
- Laser reached GHz frequency stabilities (early 2000s)
- Optical filter: BW for 50-GHz WDM channel spacings
- Efforts on increasing “spectral efficiencies“
  : To pack more information into the limited BW (~5-THz)



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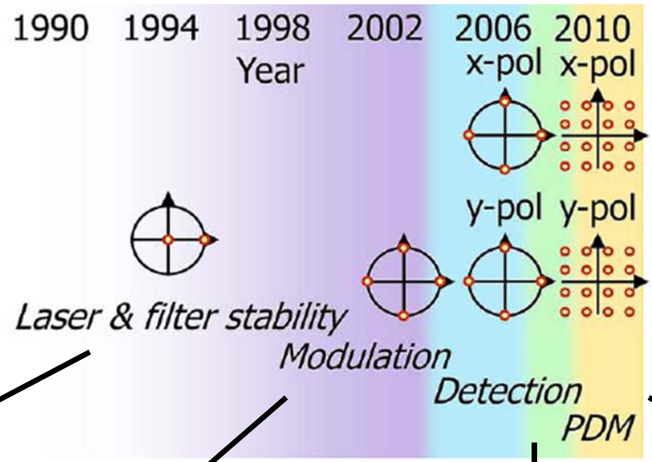
Development of optical modulation



- Single-band (C- or L-band) optical amp.

40Gb/s

- Binary & quaternary phase shift keying (BPSK, QPSK)
- Direct detection with differential demodulation (DPSK, DQPSK)

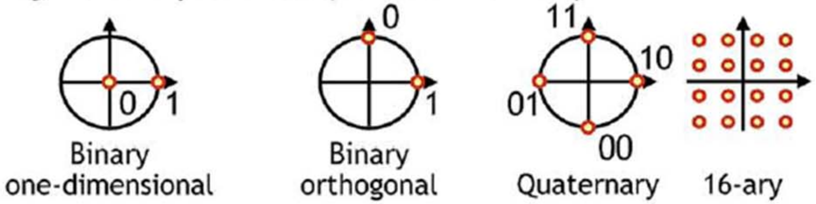
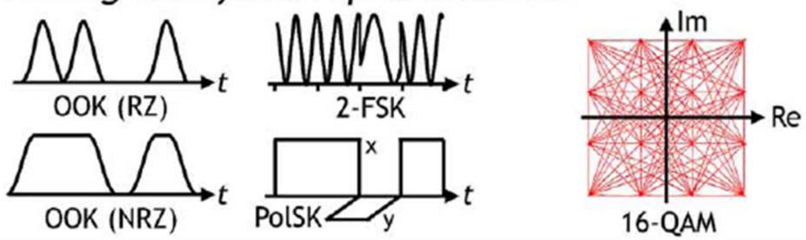
100Gb/s

- Polarization-division multiplexed (PDM) QPSK

To break Shannon limit

- Space-division multiplexed (SDM) research

Digital communication & Structure of Language

Language	*Digital communications*
Alphabets of letters {A,B,C,...,Z}, {α,β,γ,...,ω}, {0,1,2,...,9}	*Symbol alphabets (constellations)* 
Analog letter representations 'A' → A, A, A, 𝒜, 𝔄, ...	*Analog waveform representations* 
Letters arranged in series	*One symbol transmitted per symbol period*
Redundancy in words or sentences 'laguage' or 'langyage' → 'language'	*Error correcting codes* *Overhead* in time (forward error correction, FEC) or in symbol alphabet (coded modulation)
Synonym expressions (ex: use 'ponder' instead of 'think' to avoid confusion with 'sink')	*Line coding* *Overhead* in time or in symbol alphabet (ex: '11011' → {+1,+1,0,-1,-1}: 'Duobinary')

Notation

$\{a_k\}$: discrete communication symbols (constellation)

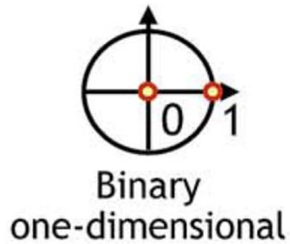
$\{x_k(t)\}$: a set of analog waveforms (corresponds to each symbols)

R_S: Sequentially transmitted symbol rate (Symbol period $T_S = 1/R_S$)

Transmit waveform $s(t) = \sum_k x_k(t - kT_S)$

M: Constellation size (number of available alphabet letters)
: Each symbol conveys $\log_2 M$ bits of information

Bit rate $R_B = R_S \log_2 M$



Ex) Simple binary symbol
M=2
Symbols: Sending no pulse & sending a pulse

Modulation format

A

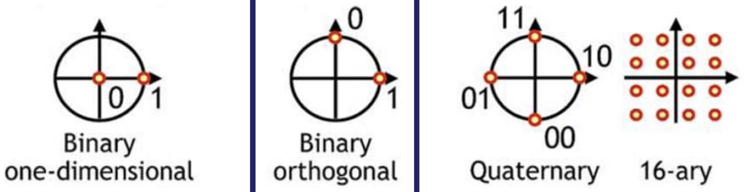
(Constellation)

Modulation format →

A, A, A, A, A

(Analog waveforms)

Examples of constellation



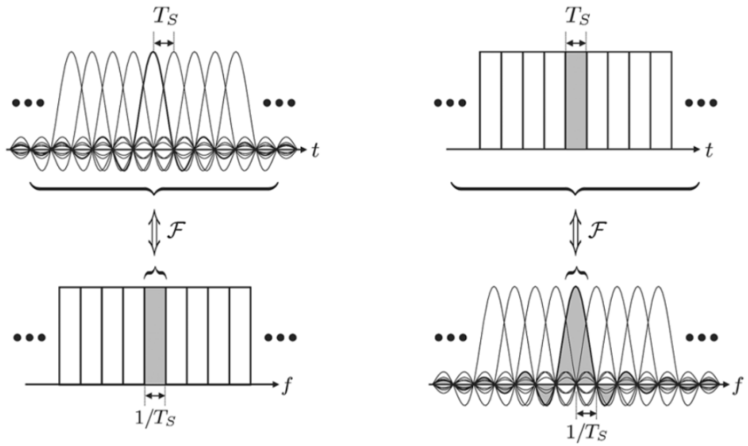
QPSK 16QAM

$$\int_{-\infty}^{\infty} dt \iint_{-\infty}^{\infty} d\vec{r}\ \vec{x}_1(t,\vec{r})\cdot\vec{x}_2^*(t,\vec{r}) =$$

$$\int_{-\infty}^{\infty} df \iint_{-\infty}^{\infty} d\vec{r}\ \vec{X}_1(f,\vec{r})\cdot\vec{X}_2^*(f,\vec{r}) = 0$$

Condition of orthogonal symbols

:No inter-symbol interference



Multiplexing

$R_B = pR_S \log_2 M$: the aggregate bit rate of multiplexed system
(p number of parallel channels)

Parallel channels
- x, y polarization of optical field (p = 2)
- p orthogonal frequencies → Frequency-division multiplexing (FDM)
- p orthogonal spatial modes

Frequency-division multiplexing (FDM)
- Example in EM wave: radio system (channel selection for frequency)

Coding

(Recall: Table 1)

Redundancy in words or sentences 'laguage' or 'langyage' → 'language'	*Error correcting codes* *Overhead* in time (forward error correction, FEC) or in symbol alphabet (coded modulation)
Synonym expressions (ex: use 'ponder' instead of 'think' to avoid confusion with 'sink')	*Line coding* *Overhead* in time or in symbol alphabet (ex: '11011' → {+1,+1,0,-1,-1}: 'Duobinary')

: Forward error correction

: Line coding

→ Inject redundancy in digital communication

Line rate: gross channel bit rate including all coding redundancy

Code rate R_c (< 1): ratio of information bit rate to line rate

Coding overhead $\mathrm{OH} = (1 - R_c)/R_c$

(OH ~ 7% for standard fiber-optic communication system)

DAC resolution

(Recall: multiplexed system)

$$R_B = pR_S \log_2 M$$

Linear dependence on R_s

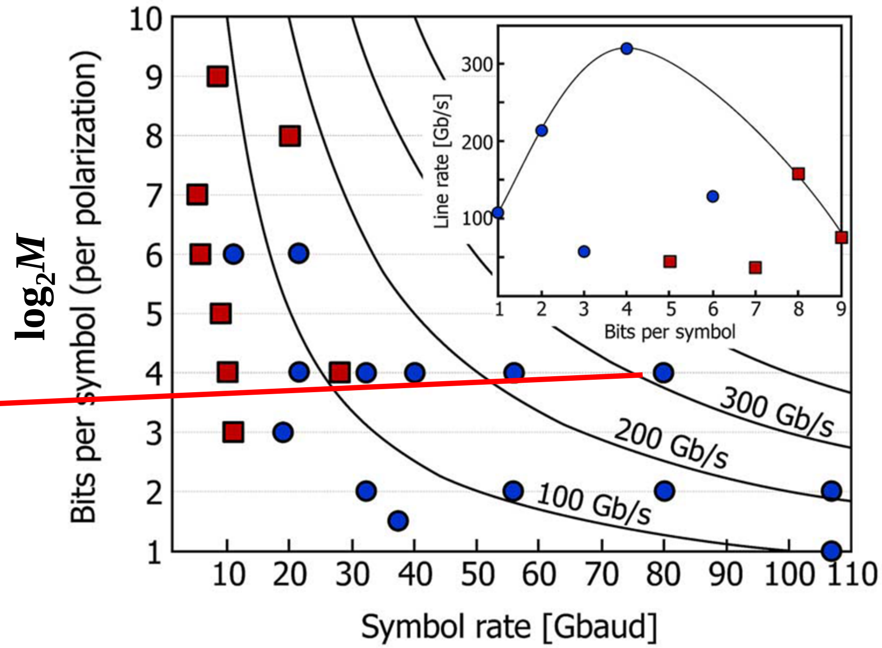
Log dependence on M

Optimized point
M = 16 (320 Gb/s line rates)
(16-QAM as modulation format)

Minimum DAC resolution

$$\log_2 \sqrt{M} \text{ bits}$$

Experimentally measured performance



Red: Digital pulse shaping
Blue: No digital pulse shaping

Optimization: M > 16 for CMOS-integrated DAC+DSP ASIC solution

ADC resolution

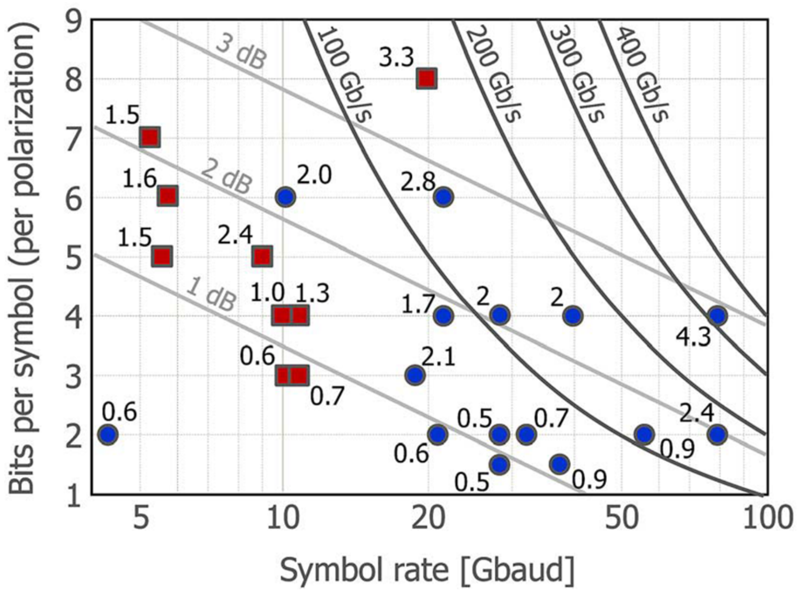
ADC resolution: specified in terms of ENoB (effective number of bits)

M	$log_2(M)$	$\sqrt{M}$	$log_2(\sqrt{M})$	ENoB [67]
4	2	2	1	~4
16	4	4	2	~5
64	6	8	3	~6
256	8	16	4	~7

+3 bits

1-dB receiver sensitivity penalty
pre-FED bit error ratio (typically 10^{-3})

→ 3 bits more than $\log_2 \sqrt{M}$



Transmitter/receiver sensitivity penalty
Gap between experimentally achieved and theoretically possible SNR (BER of 10^{-2})

Digital filter size

Linear optical impairments

: can be compensated by digital filters in receiver's DSP

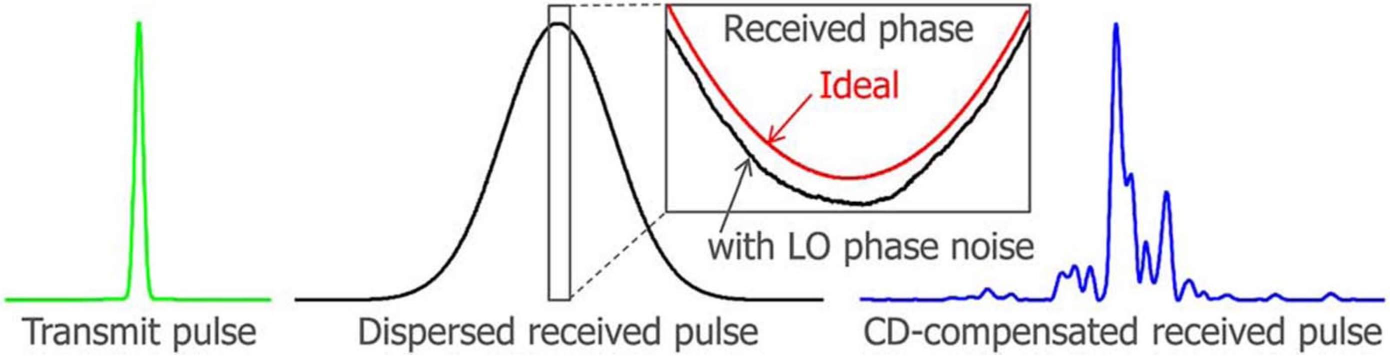
- Chromatic dispersion (CD)
- Polarization-mode dispersion (PMD)
- Etc…

CD can be compensated using a filter with inverse phase profile
Ex. 2000 km of standard single-mode fiber
→ CD compensation capability of 34 ns/nm at ~30 GBaud

Length of filter's impulse response ~ $0.032 \cdot \mathrm{CD}_{[\mathrm{ns/nm}]} \cdot R^2_{S[\mathrm{GBaud}]}$

(Adjacent-pulse overlap: due to dispersive pulse broadening)
→ scales quadratically with symbol rate

Laser phase noise



Phase noise → degrades detection performance

- Random phase fluctuation of signal & local oscillator light
- Pattern-dependent phase perturbations (due to fiber nonlinearities)

More sensitive in higher-order modulation formats

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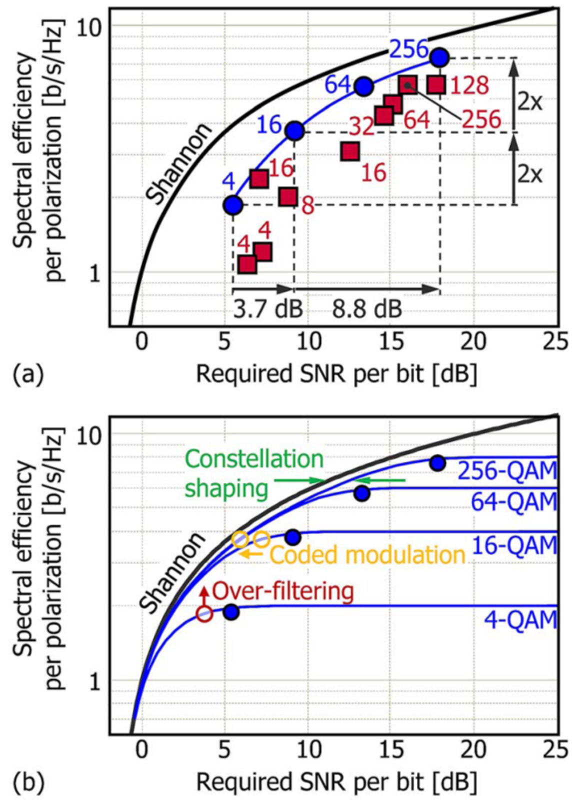
Spectral Efficiency vs. Noise

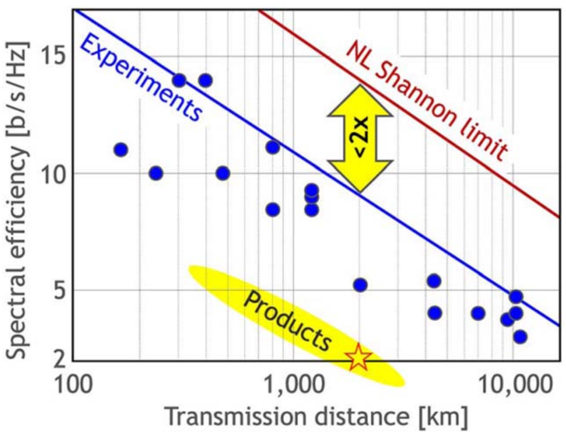
Independent of single-channel interface rates & constellation size

Trade between:
Spectral efficiency & System noise

(In linear regime)
Shannon limit: linear, additive white
Gaussian noise channel

(Impact of advanced coding)



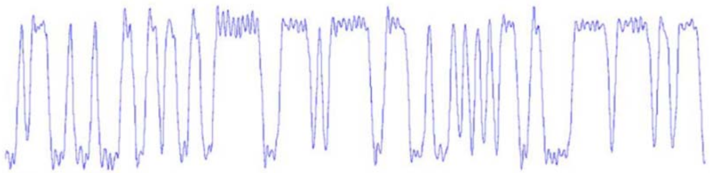


Trade between:
Spectral efficiency & Transmission reach

Spectral efficiency & pulse shaping

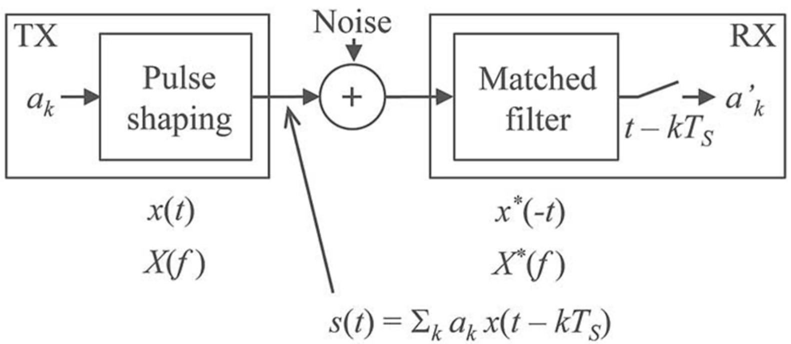
Choice of analog transmit waveforms is important aspect

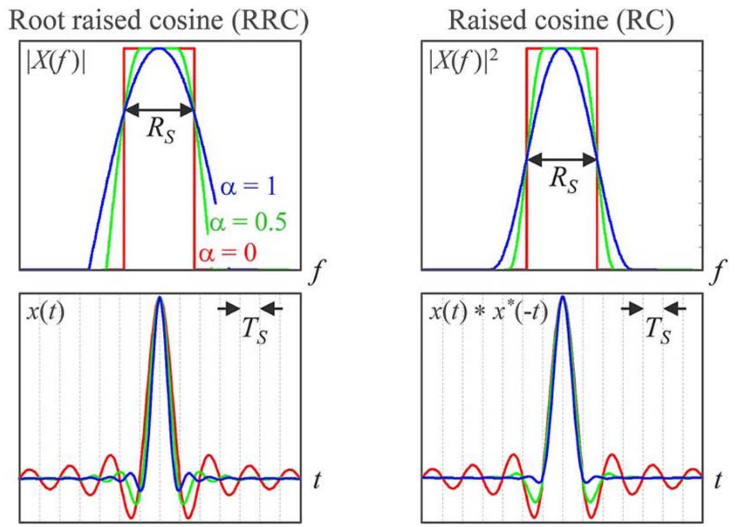
- Electronic multiplexers (to generate binary drive signals)
  : Output determine exact pulse shape



Non-return-to-zero (NRZ) waveform
: Significant amount of non-linear ISI
  Cannot be removed by linear equalization

Best solution: pulse shaping



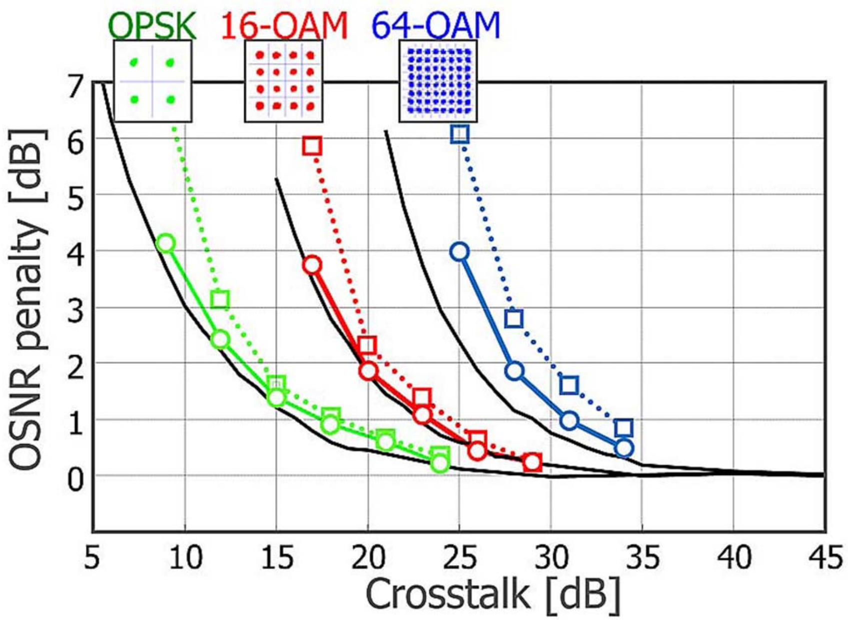


Crosstalk tolerance

Crosstalk between individual channels

- WDM crosstalk: among neighboring WDM channels

- In-band crosstalk: signals along same wavelength slot



SNR penalty vs. Crosstalk (BER of 10^{-3})

- Higher-order modulation format
  → Crosstalk ↑

- High power required to ignore crosstalk

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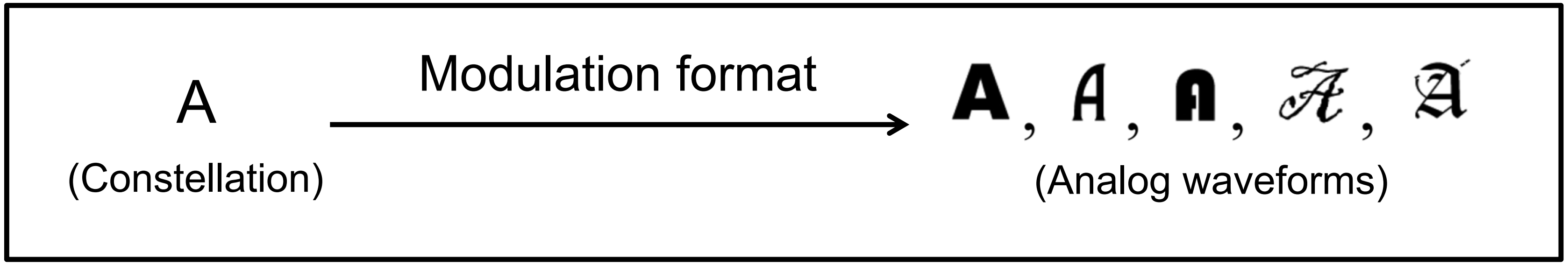
Conclusion

- Structure of optical modulation formats
  - Constellation (Digital)
  - Pulse shaping (Analog)



- Trade-off between symbol rate, constellation size, and pulse shaping effect
  - Investigate optimal point of communication performance
    ($R_B = pR_S \log_2 M$)