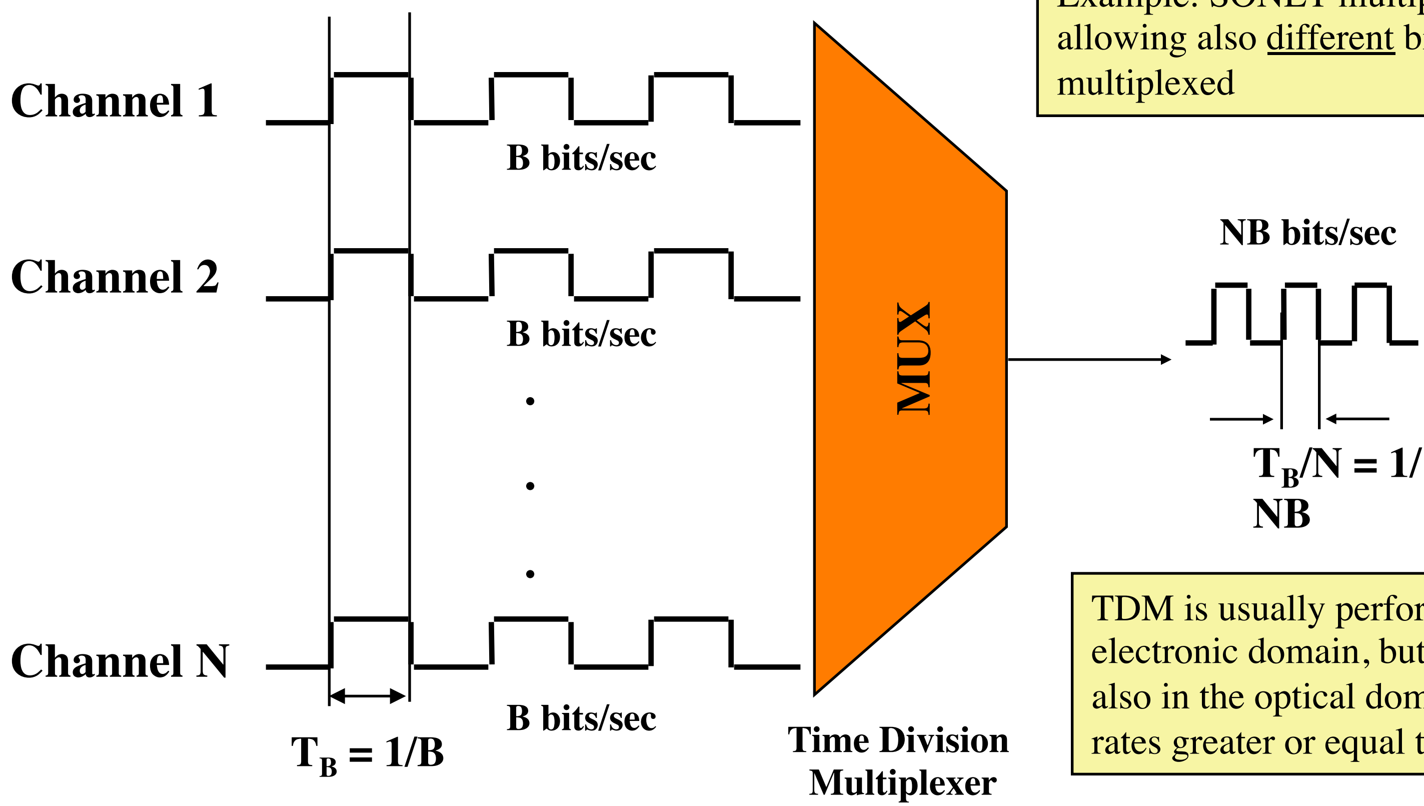
Multiplexing Techniques

- Time Division Multiplexing (TDM)

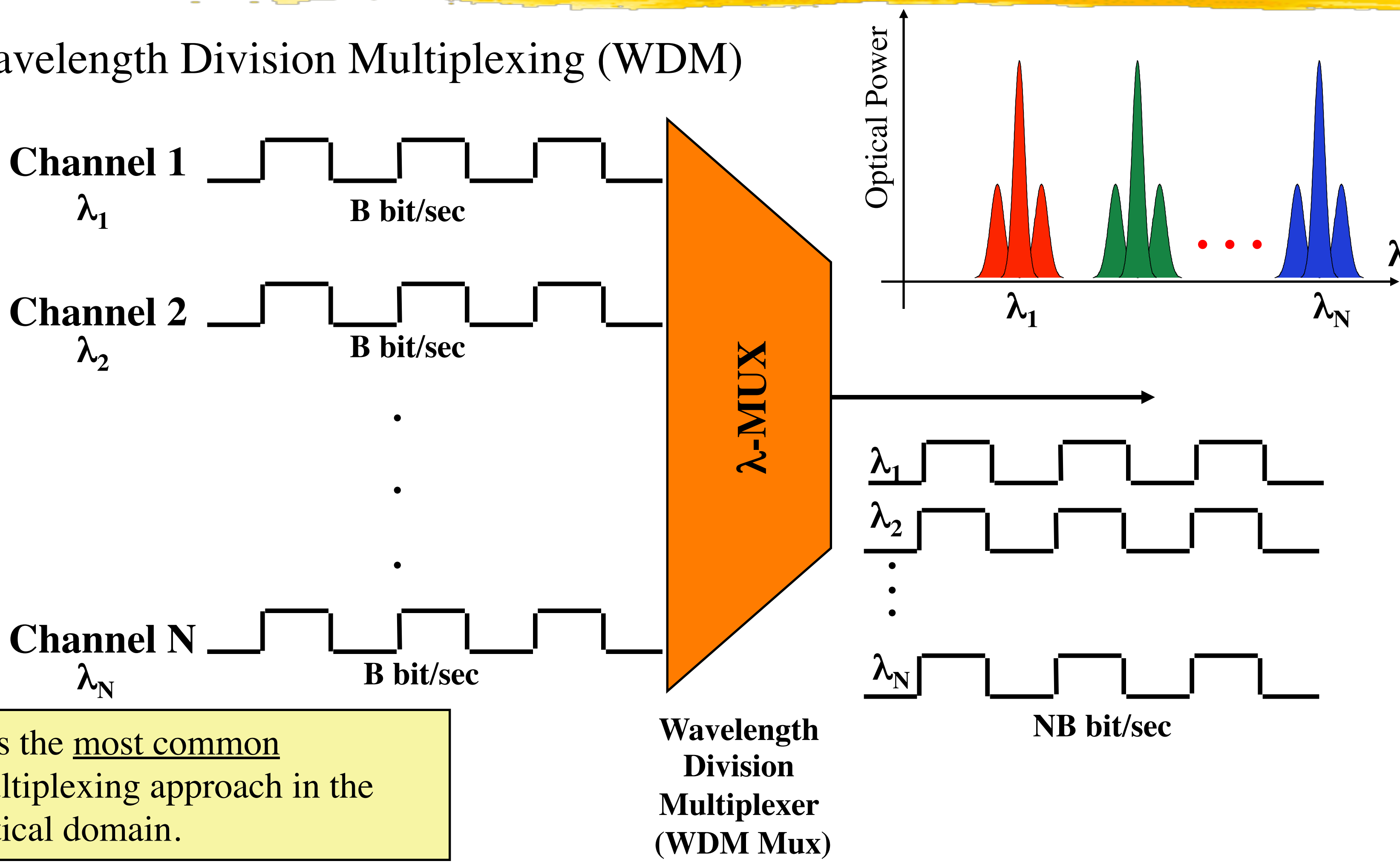
Example: SONET multiplexing, allowing also different bit rates to be multiplexed



TDM is usually performed in the electronic domain, but is is now done also in the optical domain, for bit rates greater or equal to 40Gb/s

Multiplexing Techniques

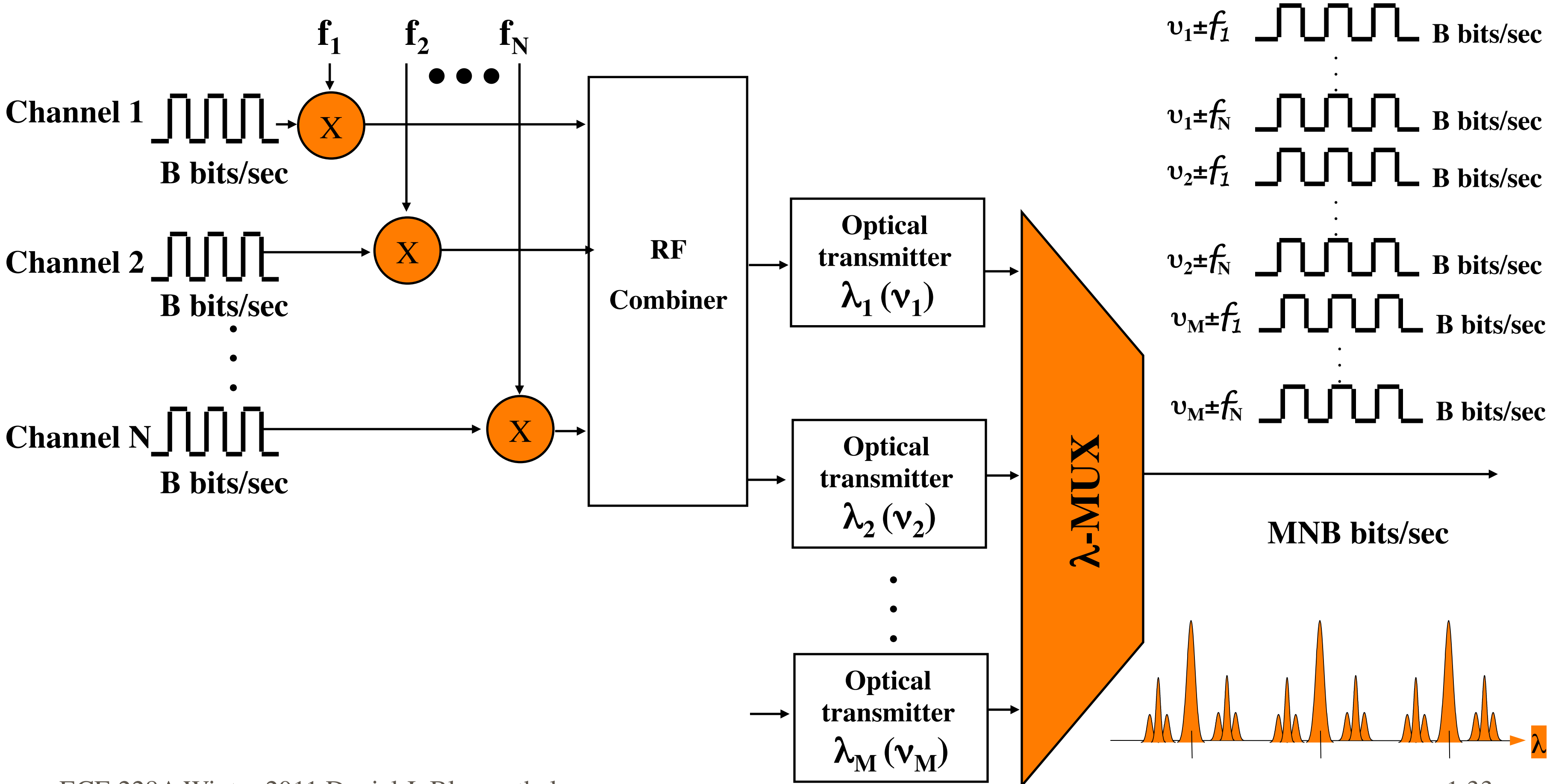
- Wavelength Division Multiplexing (WDM)



It is the <u>most common</u> multiplexing approach in the optical domain.

Multiplexing Techniques

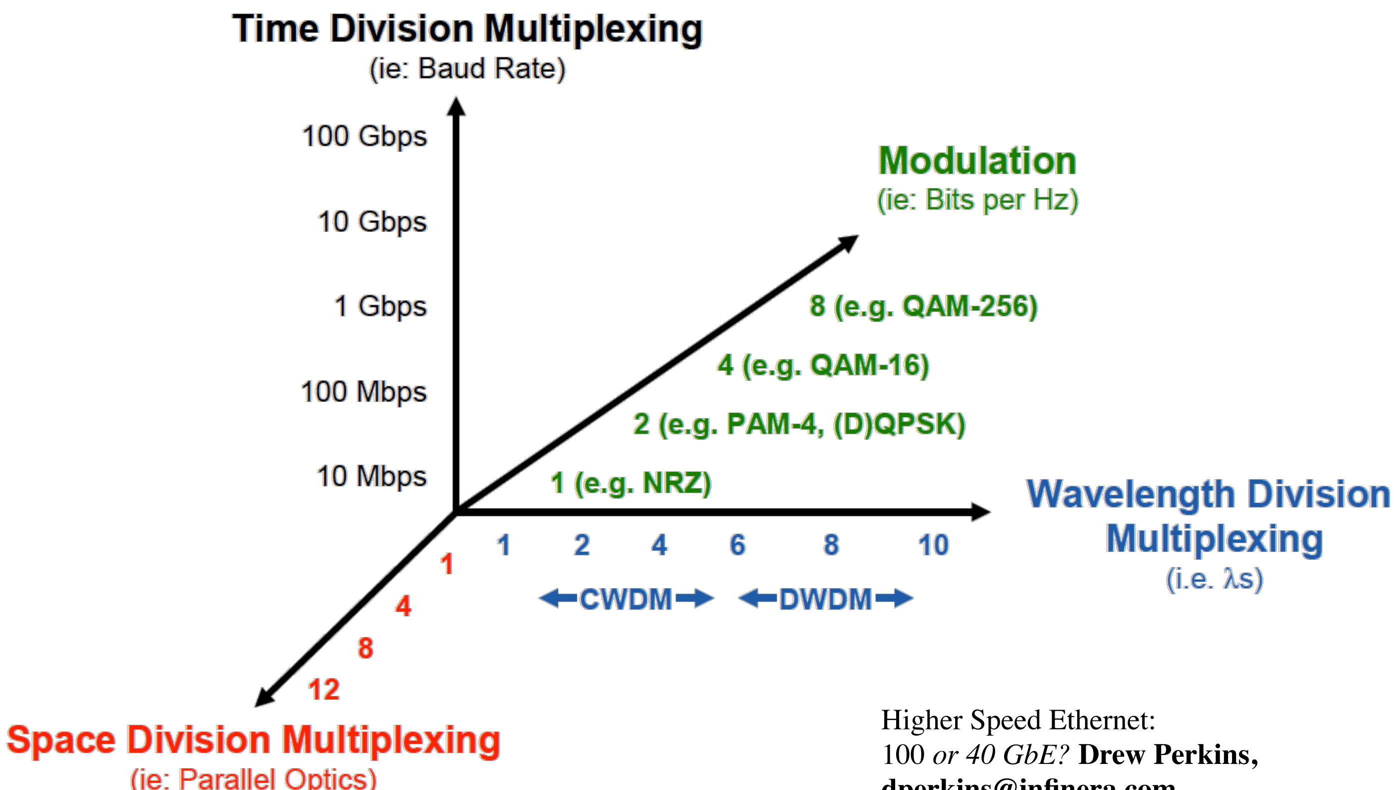
- Wavelength Division/Subcarrier Multiplexing (WDM/SCM)



Other Multiplexing and Coding Techniques

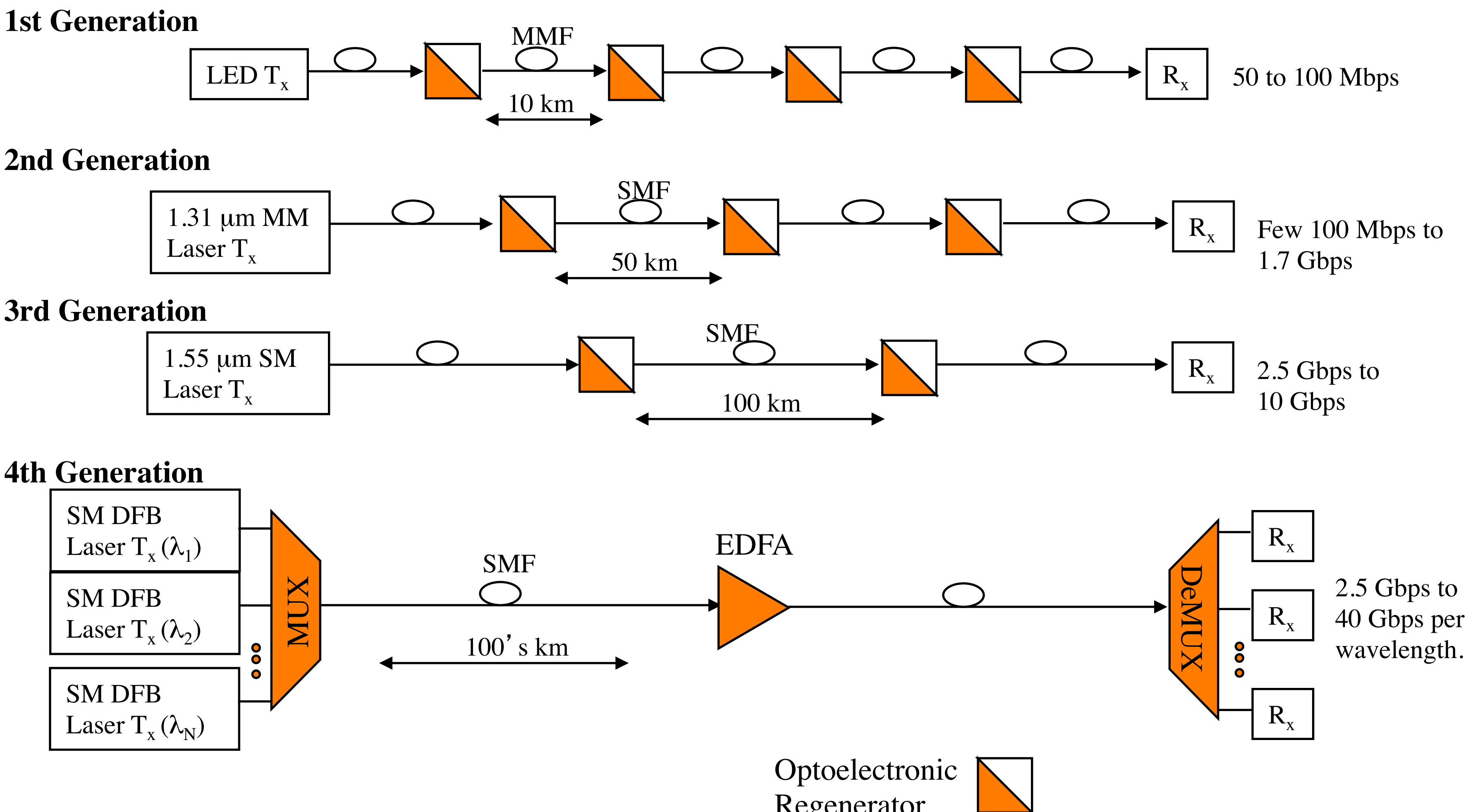
- Space Division Multiplexing:
  - use of several fibers belonging to the same bundle
- Polarization Multiplexing:
  - Using orthogonal states of polarization in fiber to transmit independent data streams
- Code Division Multiplexing
  - Initially known as spread-spectrum, a particular kind of multiplexing based on the product between the useful signals and orthogonal pseudorandom sequences (mostly used in RF/wireless applications, like in third generation wireless phone)
- Multilevel Coding
  - Bandwidth efficient way to increase channel bit-rate without requiring more modulation bandwidth.

Coding and Modulation

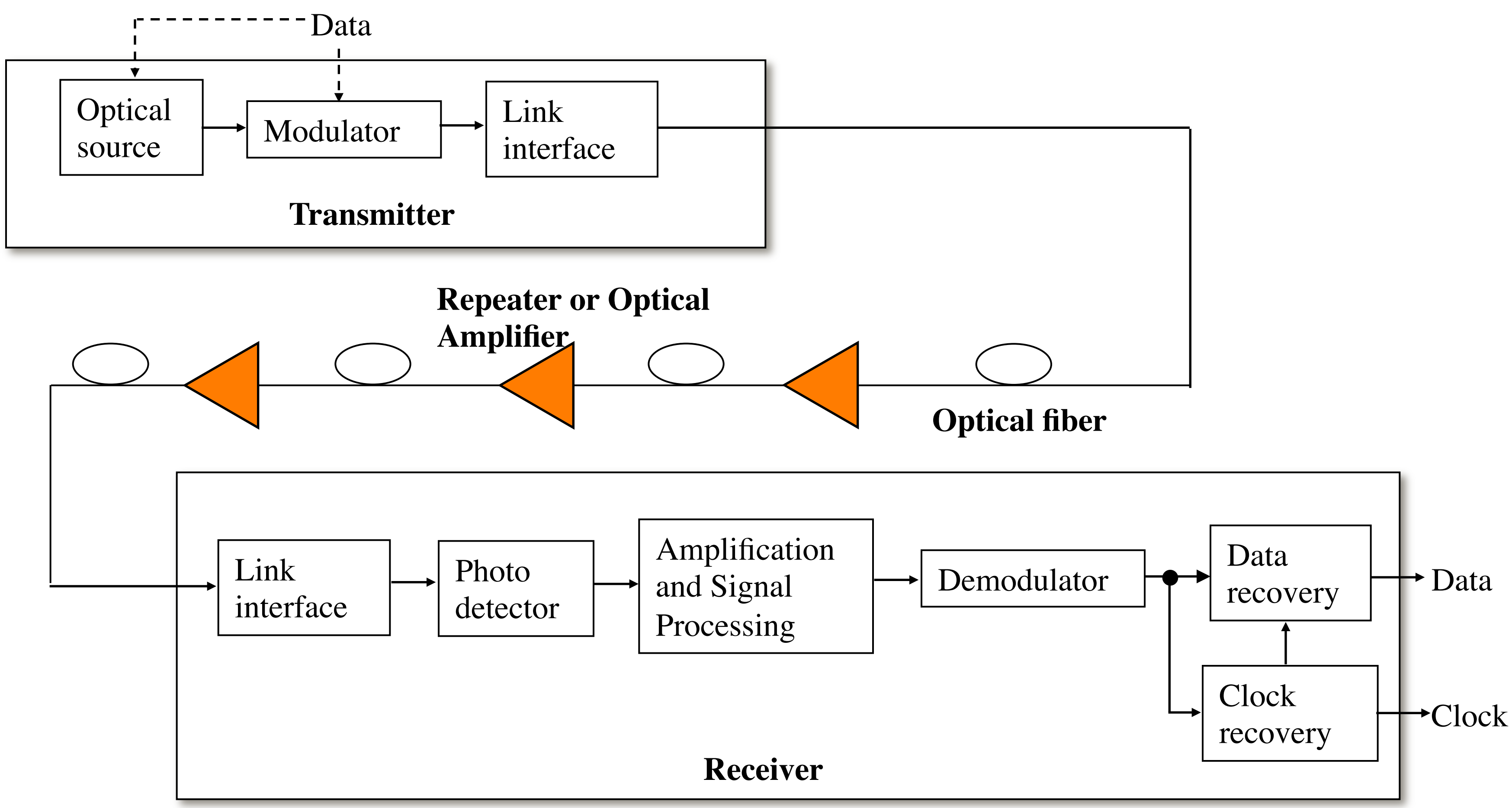


Higher Speed Ethernet:
100 *or 40 GbE?* **Drew Perkins, dperkins@infinera.com**

DWDM Link Evolution



Basic Fiber Optic Point-to-Point Link

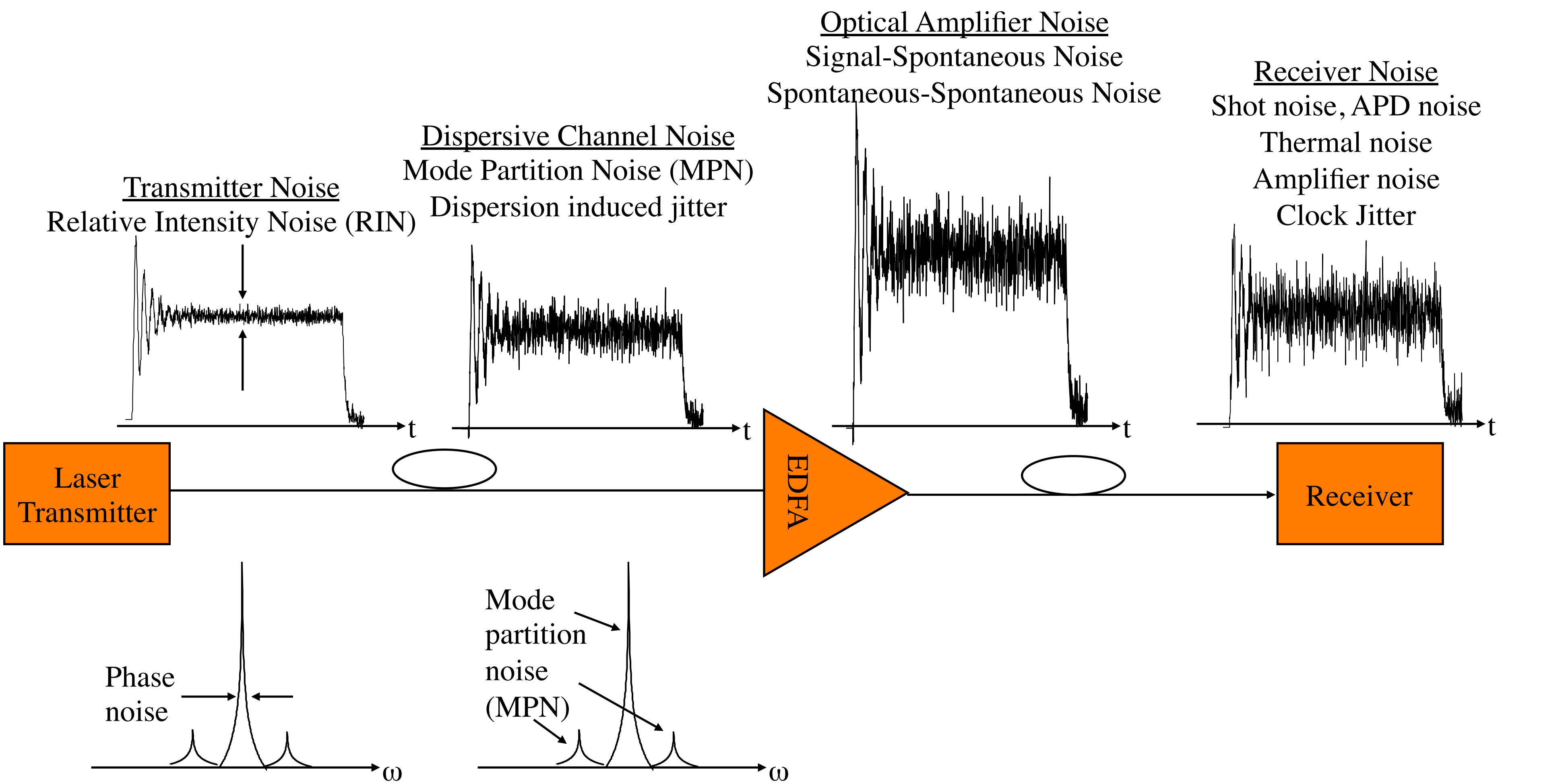


Link Capacity and Spectral Efficiency

- Capacity of an optical communications channel is the maximum bit rate that can be transmitted without error for a given noise, bandwidth and power.
- Capacity can be calculated independent of modulation, coding or decoding technique
- For a WDM (Wavelength Division Multiplexed) optical communications system

$$S = \text{Spectral Efficiency} = \frac{\text{Capacity per Channel}}{\text{Channel Spacing}} = \frac{C}{\Delta f} = \frac{\text{Bits/Second}}{\text{Hz}}$$

Signal to Noise Ratio (SNR)



Modulation Basics (I)

- Define
  - R_b = bit rate = bits/second
  - R_c = added redundancy per bit to improve SNR = baud = symbols/second
  - B = occupied bandwidth per channel
  - M = number of points in signal constellation
- Binary Modulation
  - One bit per symbol
- Non-Binary Modulation
  - More than one bit per symbol
- No inter-symbol interference (ISI)
  - $R_s \leq B$
- Error correction
  - $R_c \leq 1$
- No error correction
  - $R_c = 1$

Information bit rate per channel in one polarization state

$$R_b = R_s R_c \log_2 M$$

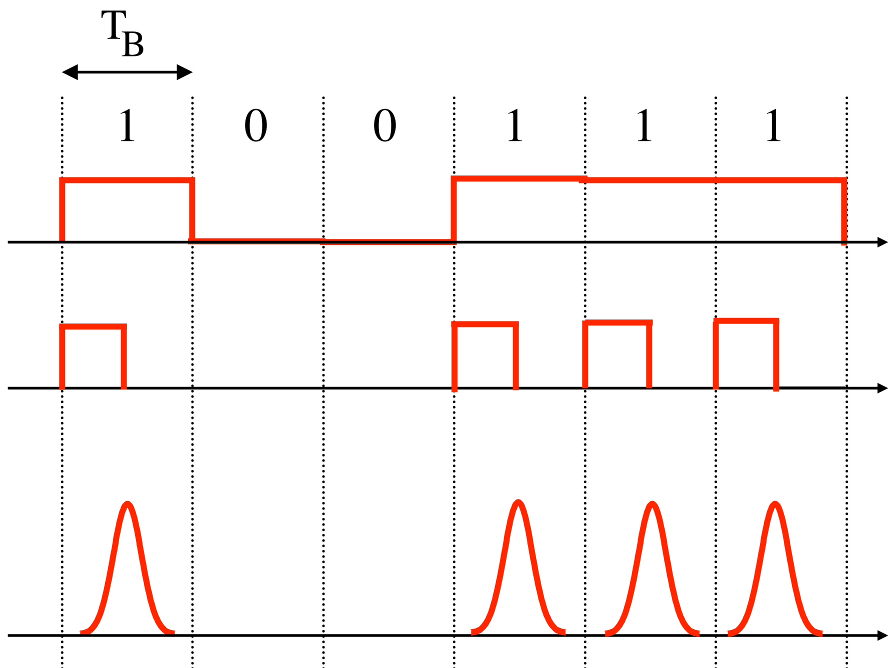
Binary Intensity Modulation

- The primary modulation format used for commercially deployed optical systems are intensity modulation (optical power modulation)

Non Return to Zero
NRZ

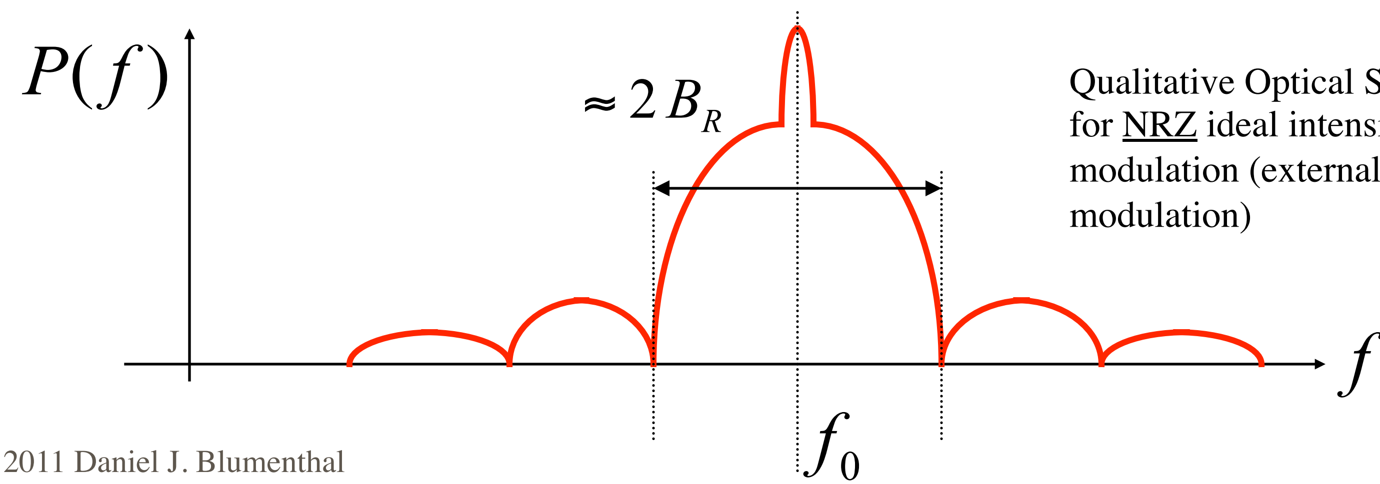
Return to Zero
RZ (50 % dc)

Pulsed
RZ (gaussian-like or soliton-like pulses, can be less than 50% dc)



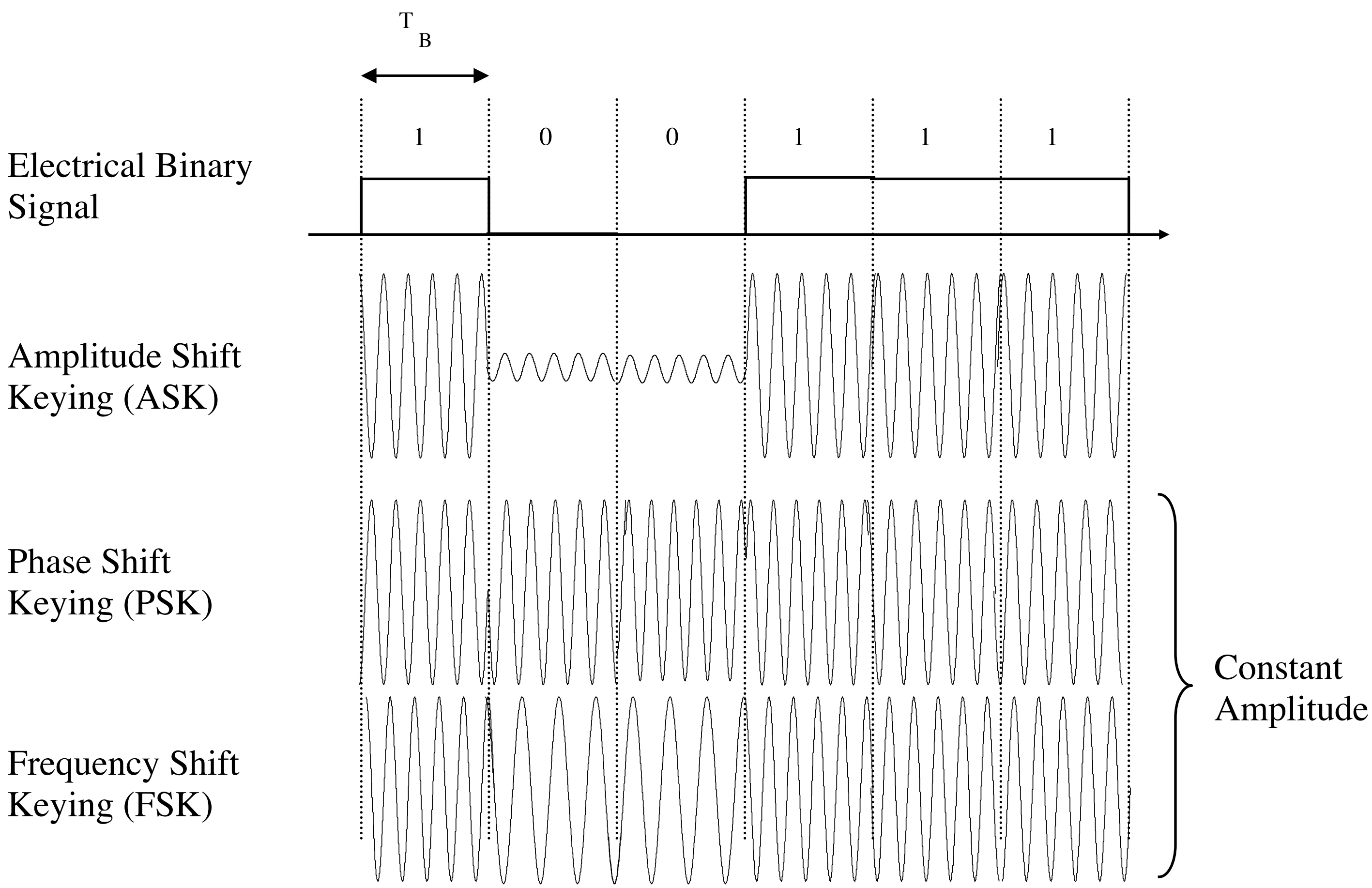
Optical spectrum for intensity modulation

- If the intensity modulation is imposed to the optical signal together with unwanted phase or frequency modulation (e.g chirp under direct laser modulation, excess laser phase noise)
  - The resulting optical spectrum is larger than the bit rate
- If the modulation is a (nearly) pure intensity modulation, without any accompanying phase/frequency shift (e.g. external modulation)
  - The resulting spectrum has a primary lobe that occupies the order of the bit rate



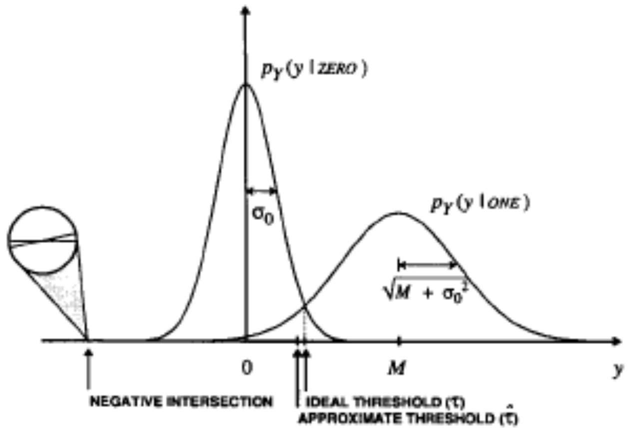
Qualitative Optical Spectrum for NRZ ideal intensity modulation (external modulation)

Coherent Binary Modulation

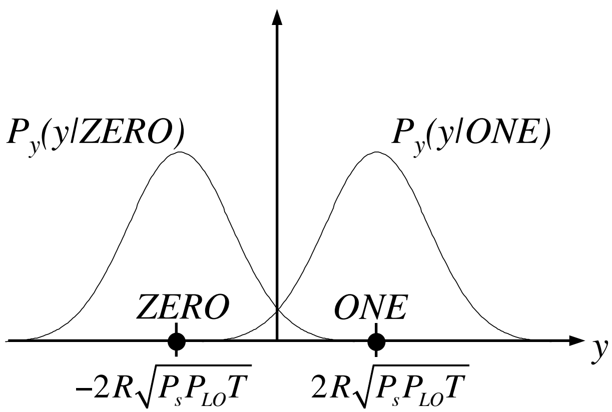


Binary Signal Constellations

Binary Intensity Modulation/Direct Detect (IM/DD)



Two-Level PSK



M = average power in 1 bit
σ_0 = variance of signal independent noise
P_s = average signal power
P_{LO} = average local oscillator power
T = bit period

Modulation Constellations

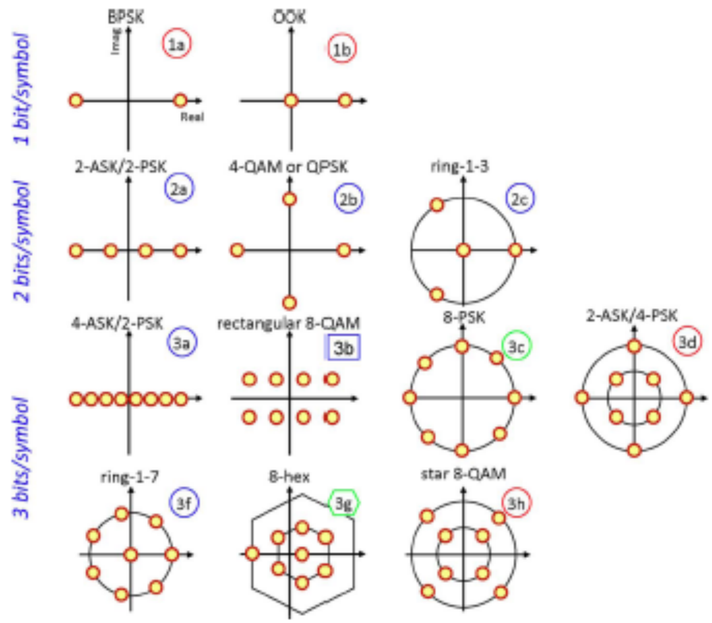


Fig. 42. Examples of constellations with $M = 2$, $M = 4$, and $M = 8$ points.

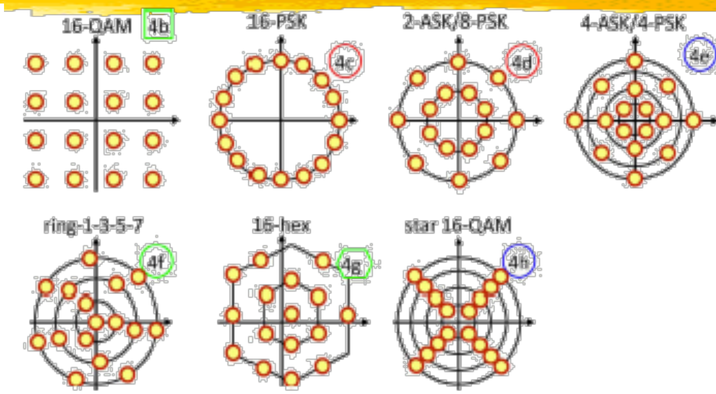


Fig. 44. Constellations with $M = 16$ points.

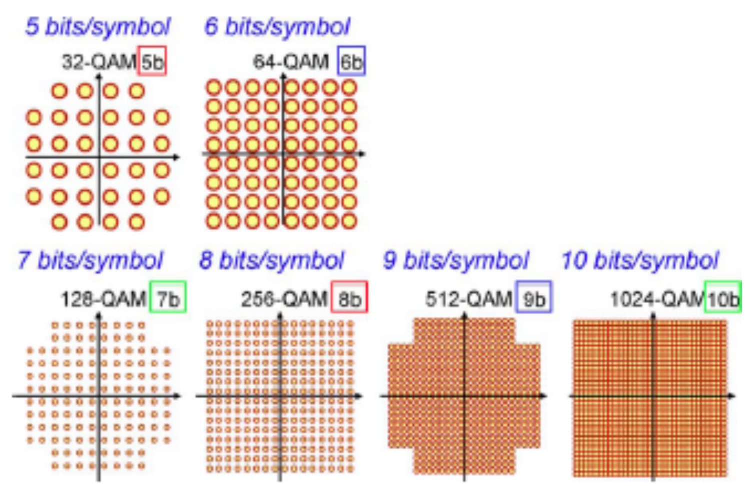


Fig. 47. QAM constellations with 32, 64, 128, 256, 512, and 1024 points.

Capacity Limits of Optical Fiber Networks, René-Jean Essiambre et. al., JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 28, NO. 4, FEBRUARY 15, 2010