Lecture 1: Overview of Optical Communications Links and Intro to Photodetection

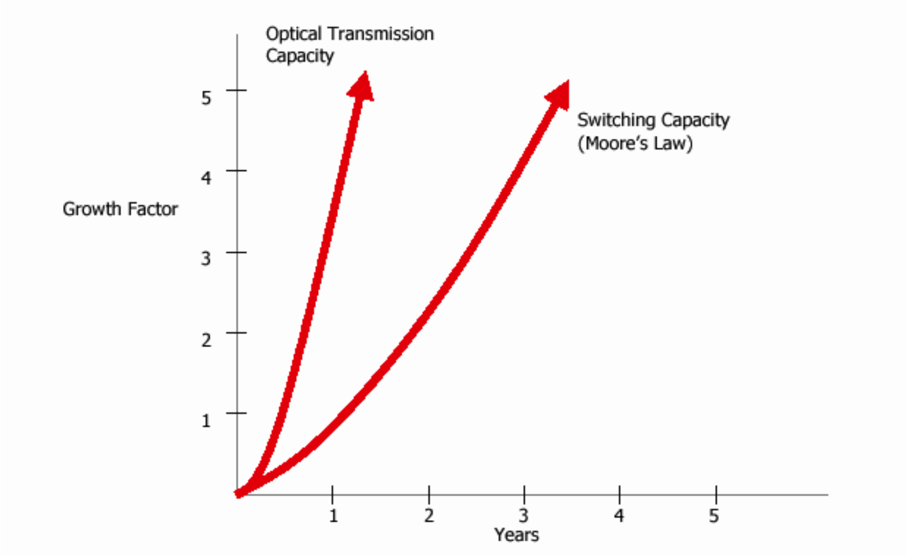
Overview of Optical Communications Links

Fiber-Optic Network Applications

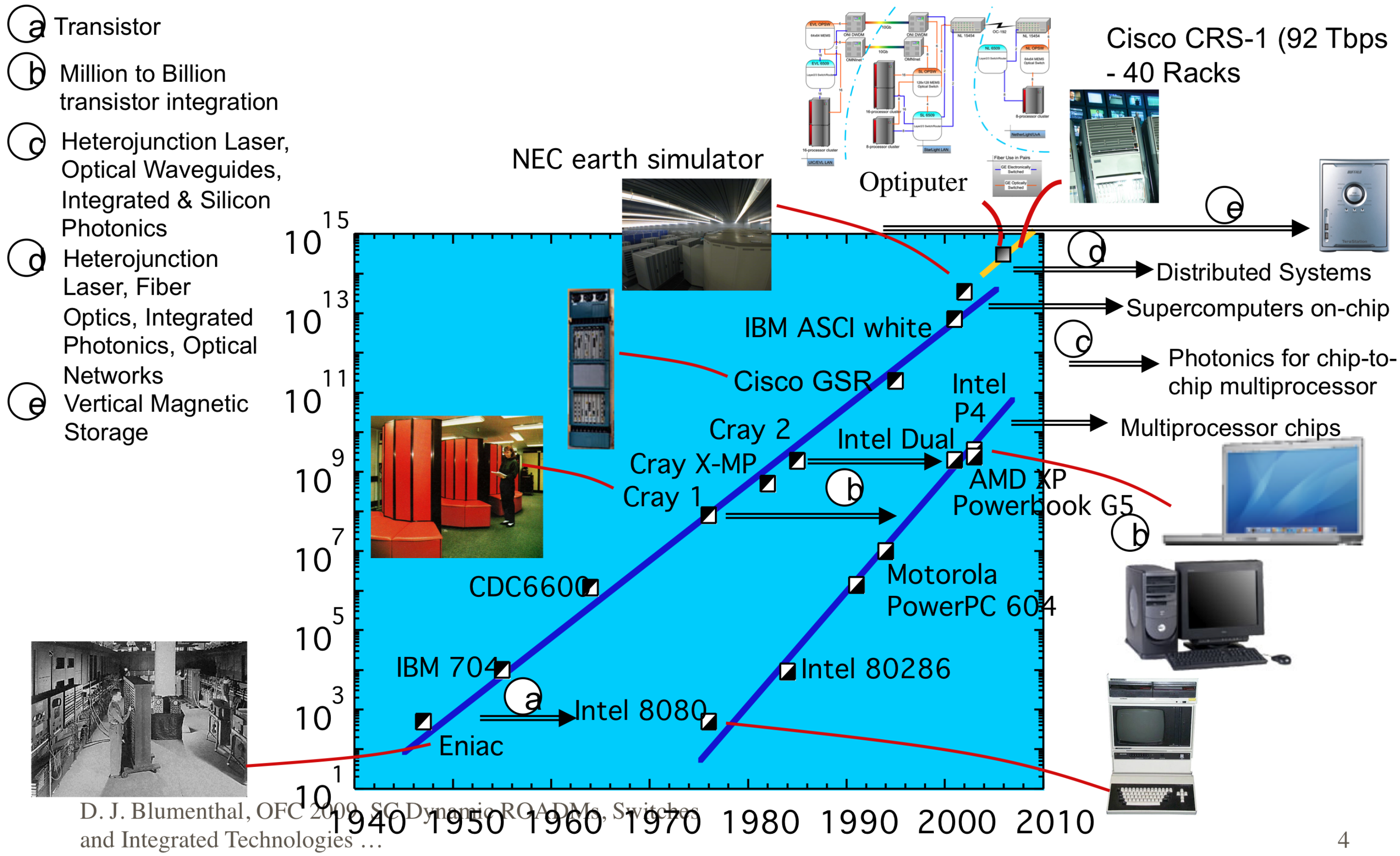
- Main application: digital transmission
  - Voice, telephone
  - Data
    - IP Networks
    - ATM, Gigabit Ethernet, FDDI, etc.
    - Distributed Computing and Databases
    - Video, Multimedia
- Microwave Photonics
  - Fiber/Wireless
  - Hybrid Fiber/Coax
- Other applications
  - Fiber/Wireless
  - Hybrid Fiber/Coax

Note:

Traffic generated by data-centric application (mainly IP) is rapidly surpassing the voice-centric traffic

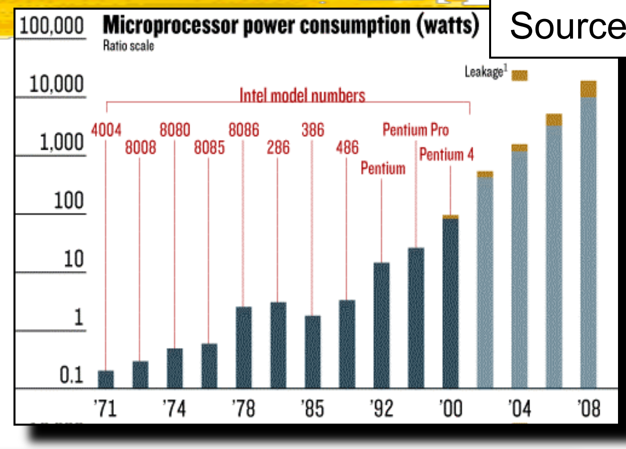


Technology Push and Integration Trends

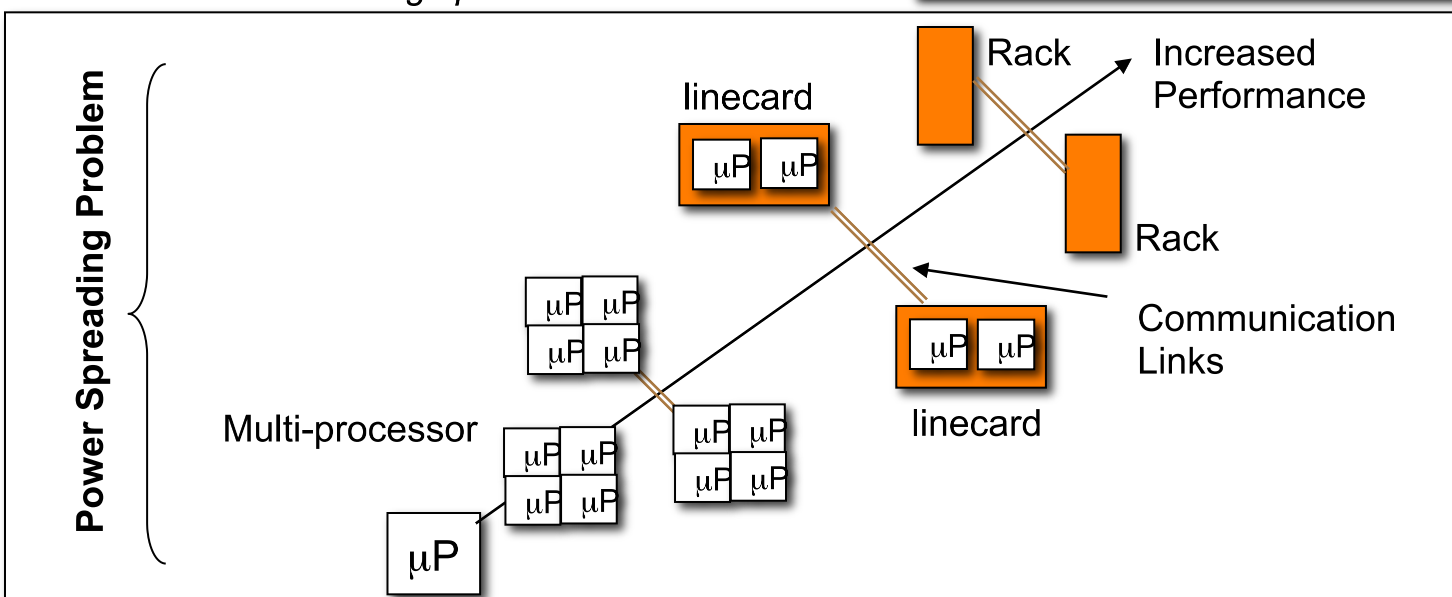


Power and Size: The Next Frontier

- *Decreased transistor size, 2x transistors on chip every 18 months, increased frequency*
- *Leakage current is huge problem, chips (hence systems) become power constrained*
- *New transistor technologies aim to decrease leakage current but requires new processing infrastructure. Costly to roll over to new foundries from current.*
- *Moving to multi-processor cores to keep up performance without increasing speed*



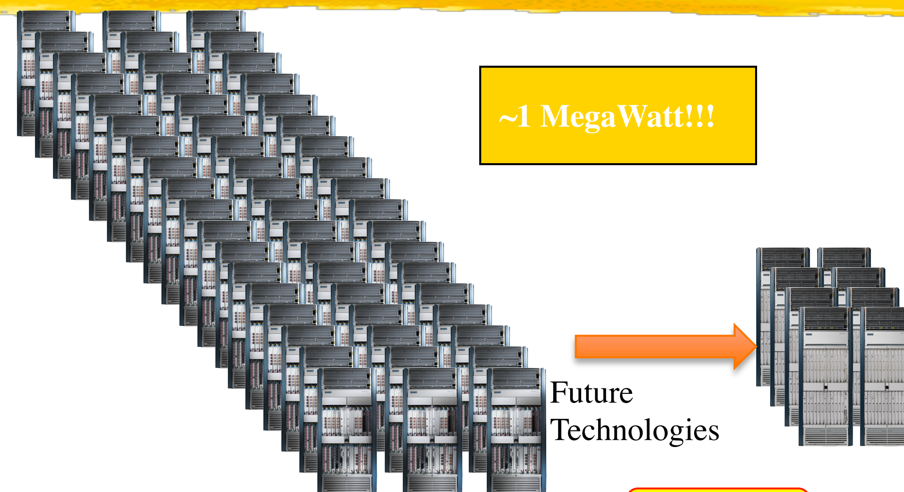
Source: Intel

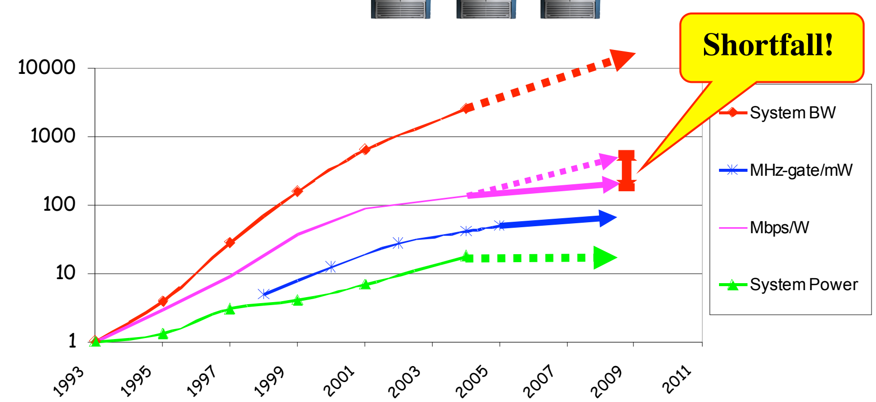


The Power Bottleneck

Maximum configuration: 92Tbps
➔ 72 x LC chassis + 8 x Fabric chassis

- Transistors – power dissipated on every bit
  - Faster frequency more power dissipated
  - Power scales linearly with message length
  - Regenerative technology
- Optics
  - Pay initial bias power price
  - Faster data frequency does not add power (due to data relative to carrier frequency)
  - Switching on boundaries only
  - Loss and SNR is key issue
  - Regeneration

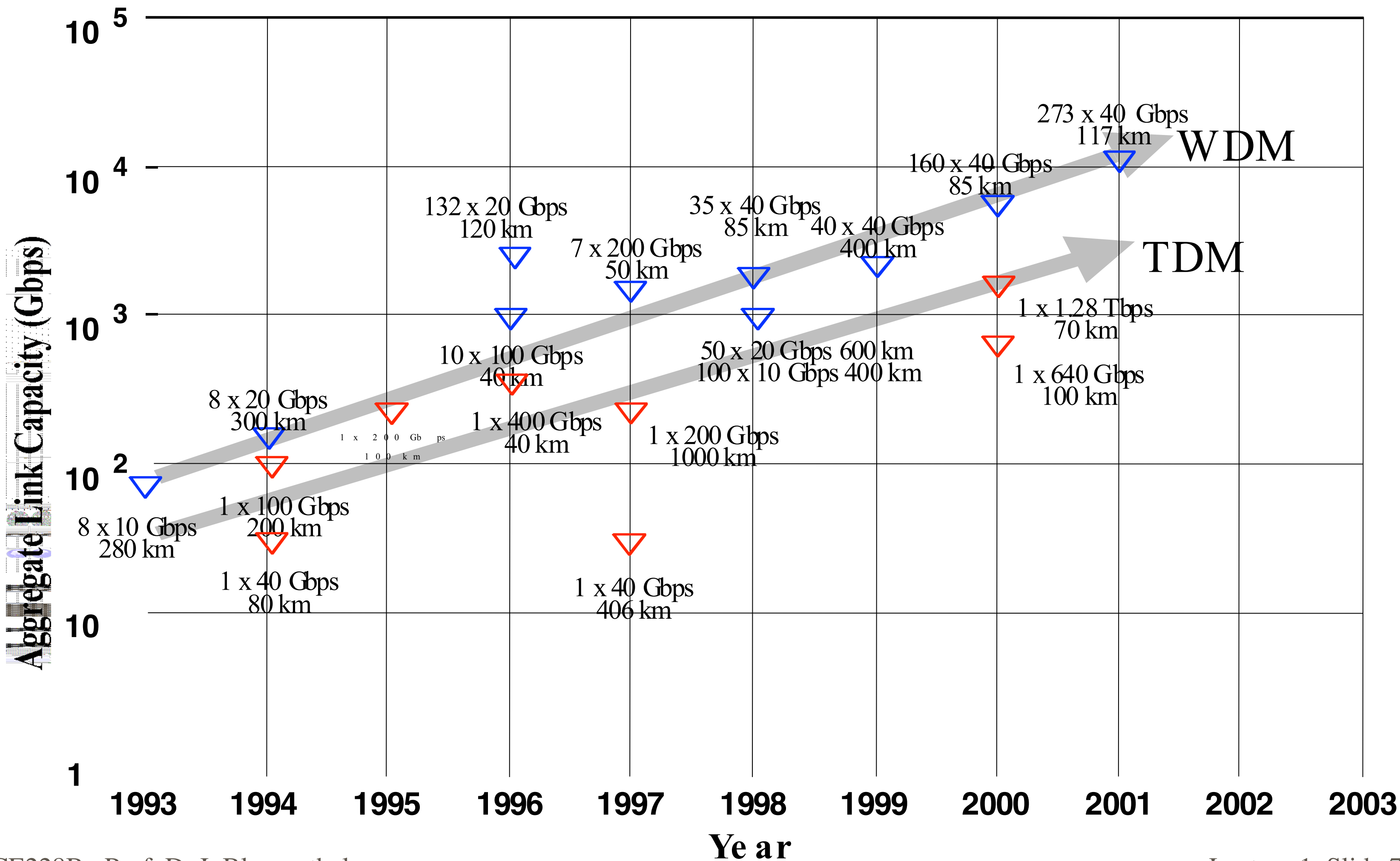




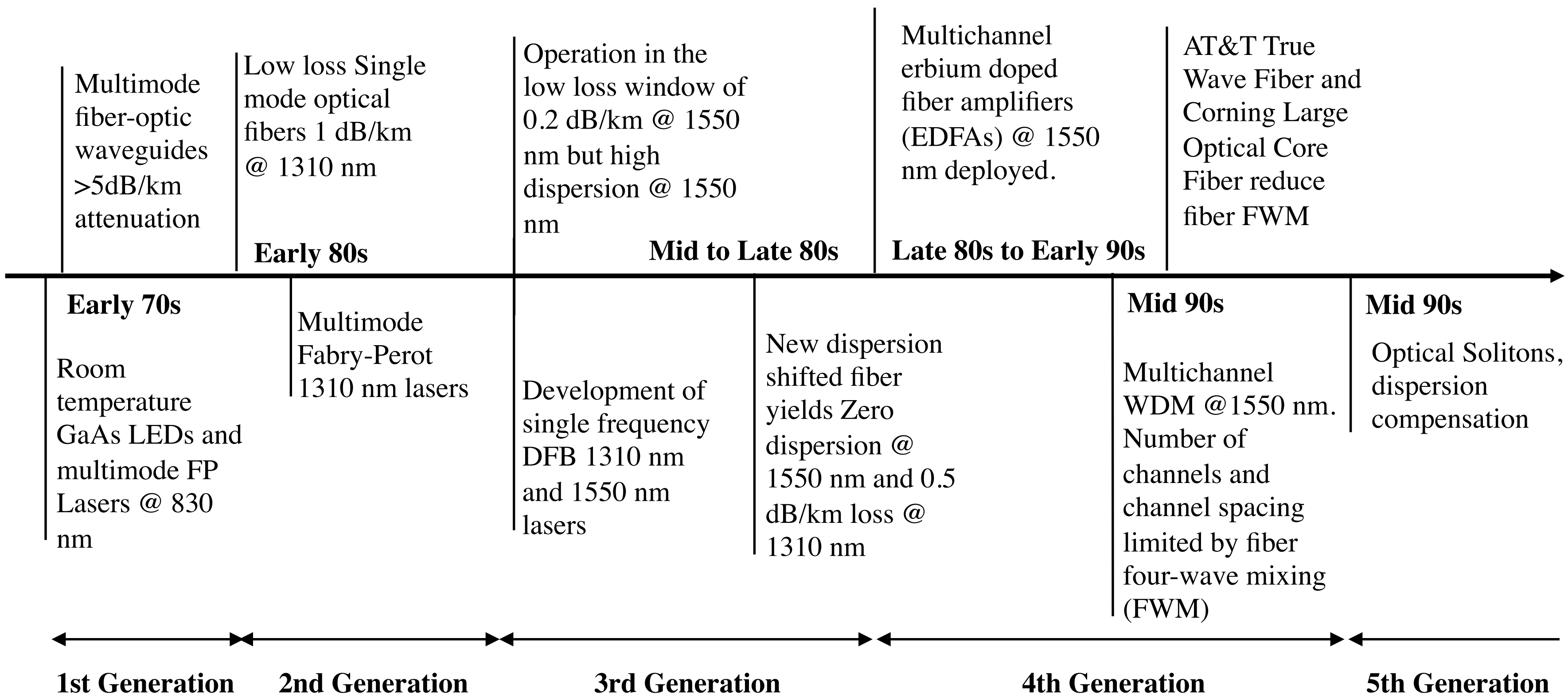
Shortfall is overcome by architectural innovation and trading off: Performance, functionality, programmability, physical size/density ➔ Very hard to sustain long-term

From Garry Epps, Cisco Systems

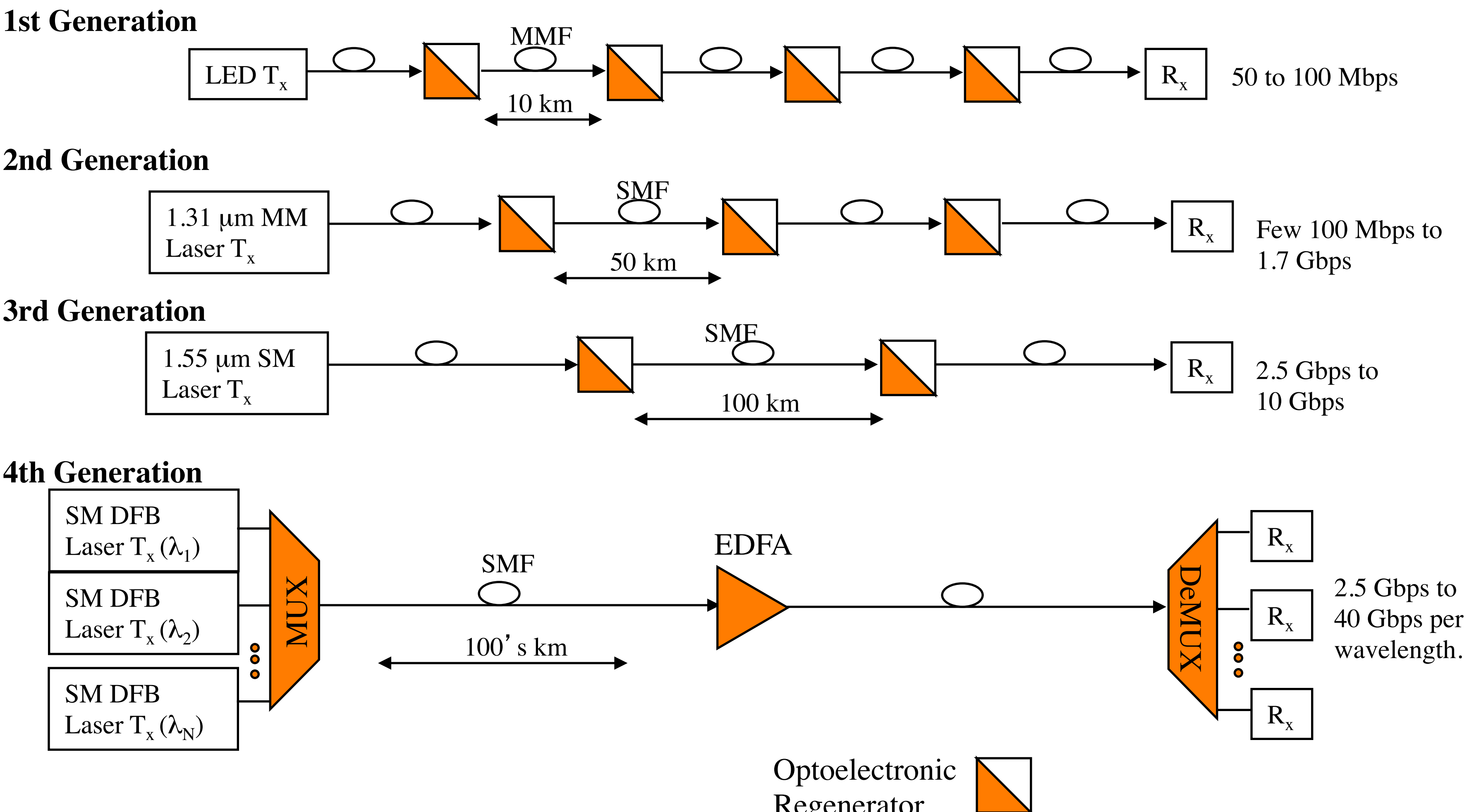
Transmission Bandwidth Evolution



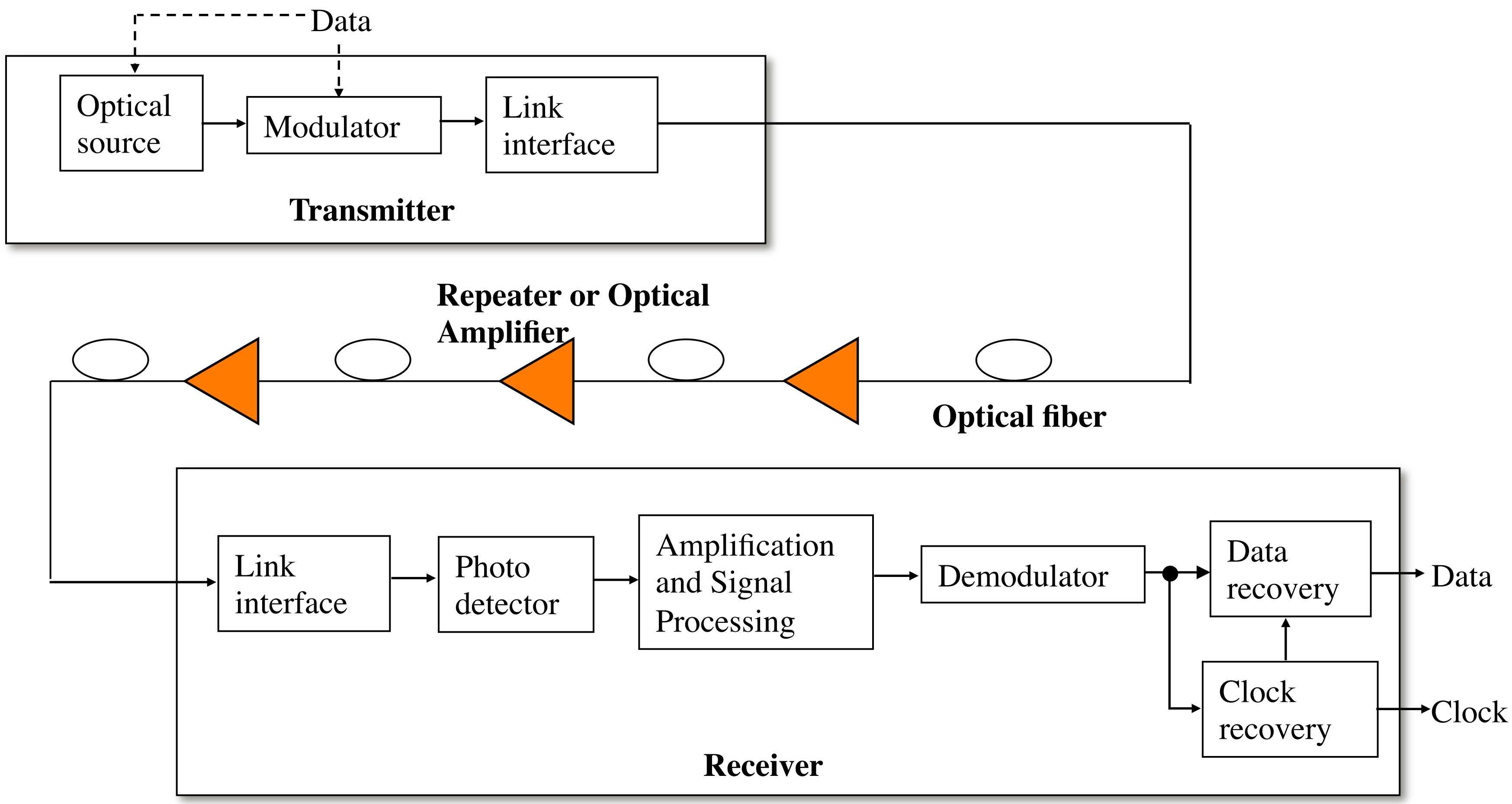
Evolution of Fiber-Optic Point-to-Point Transmission



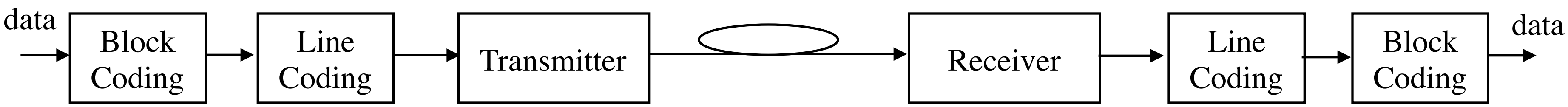
DWDM Link Evolution



Basic Fiber Optic Point-to-Point Link



Basic Communication System



Block Coding
- Error Correction
- Redundancy
- Overcome noise and transmission impairments
- E.g. FEC, Turbo-Codes

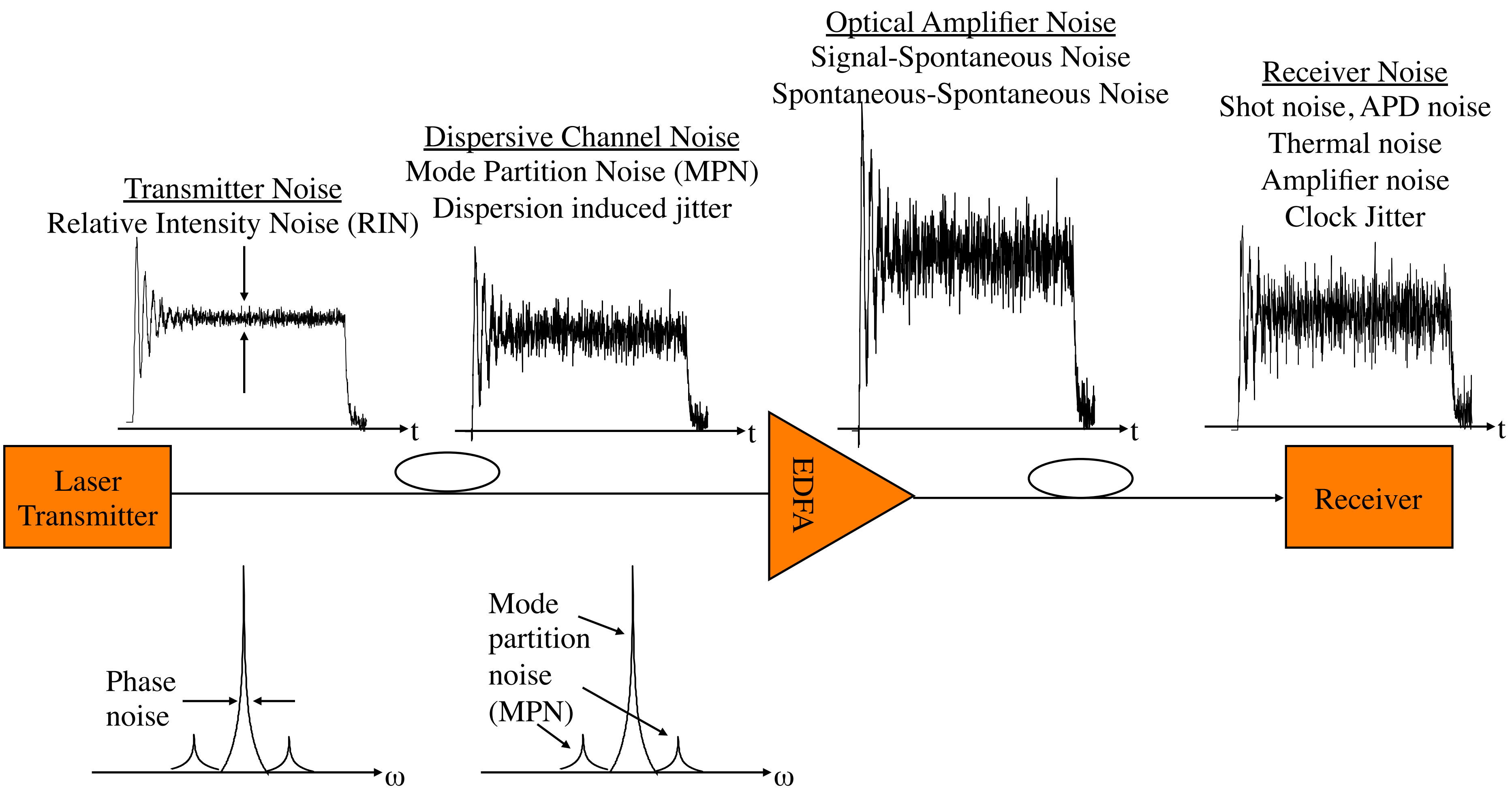
Line Coding
- DC balance
- Redundancy
- E.g Manchester Codes

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)

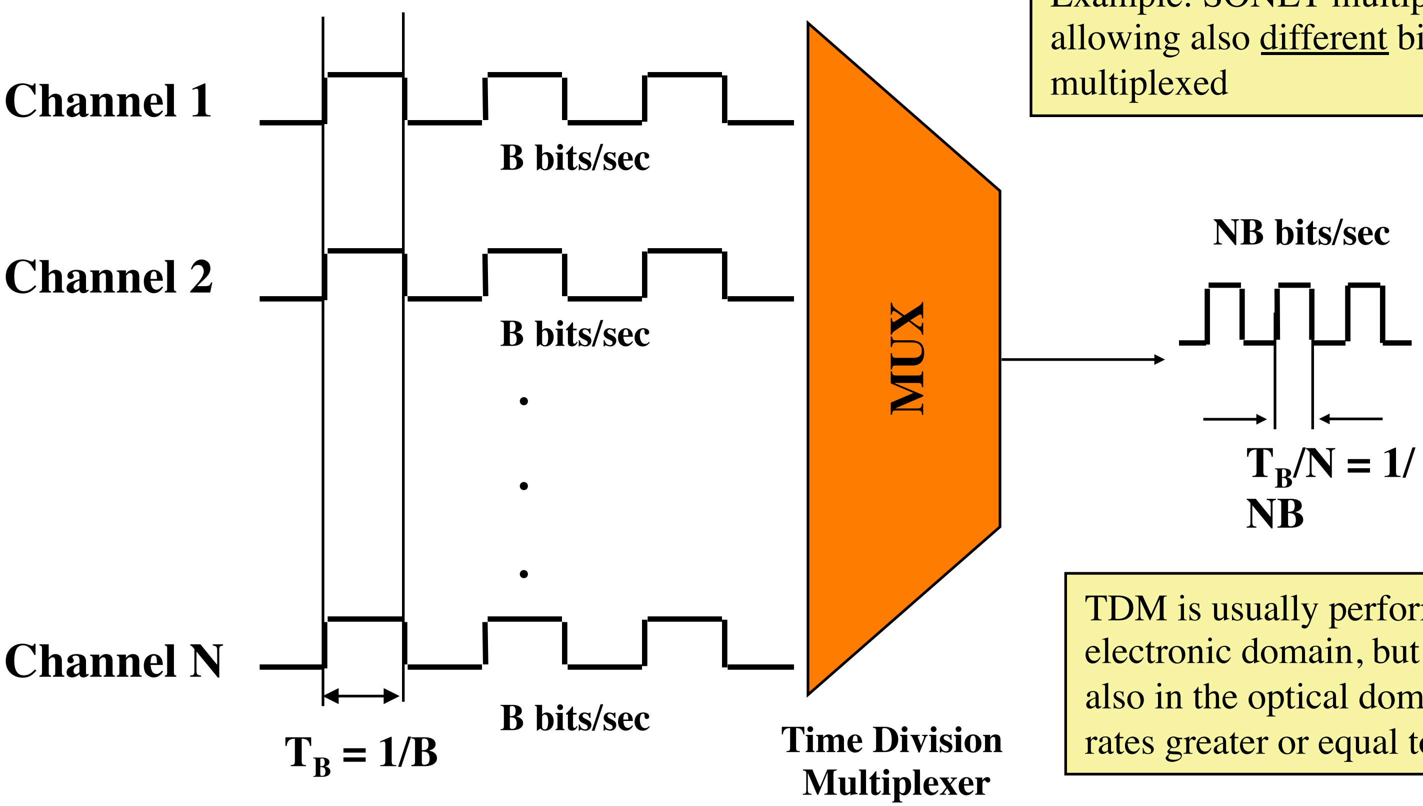


Multiplexing Techniques

Multiplexing Techniques

- Multiplexing is the technique used to carry several different information channels on a common physical medium. The standard techniques are:
  - Time Division Multiplexing (TDM)
  - Frequency Division Multiplexing, indicated as "Wavelength Division Multiplexing" (WDM) in optics
  - Space Division Multiplexing (SDM)
  - Code Division Multiplexing (CDMA)
  - Multilevel coding

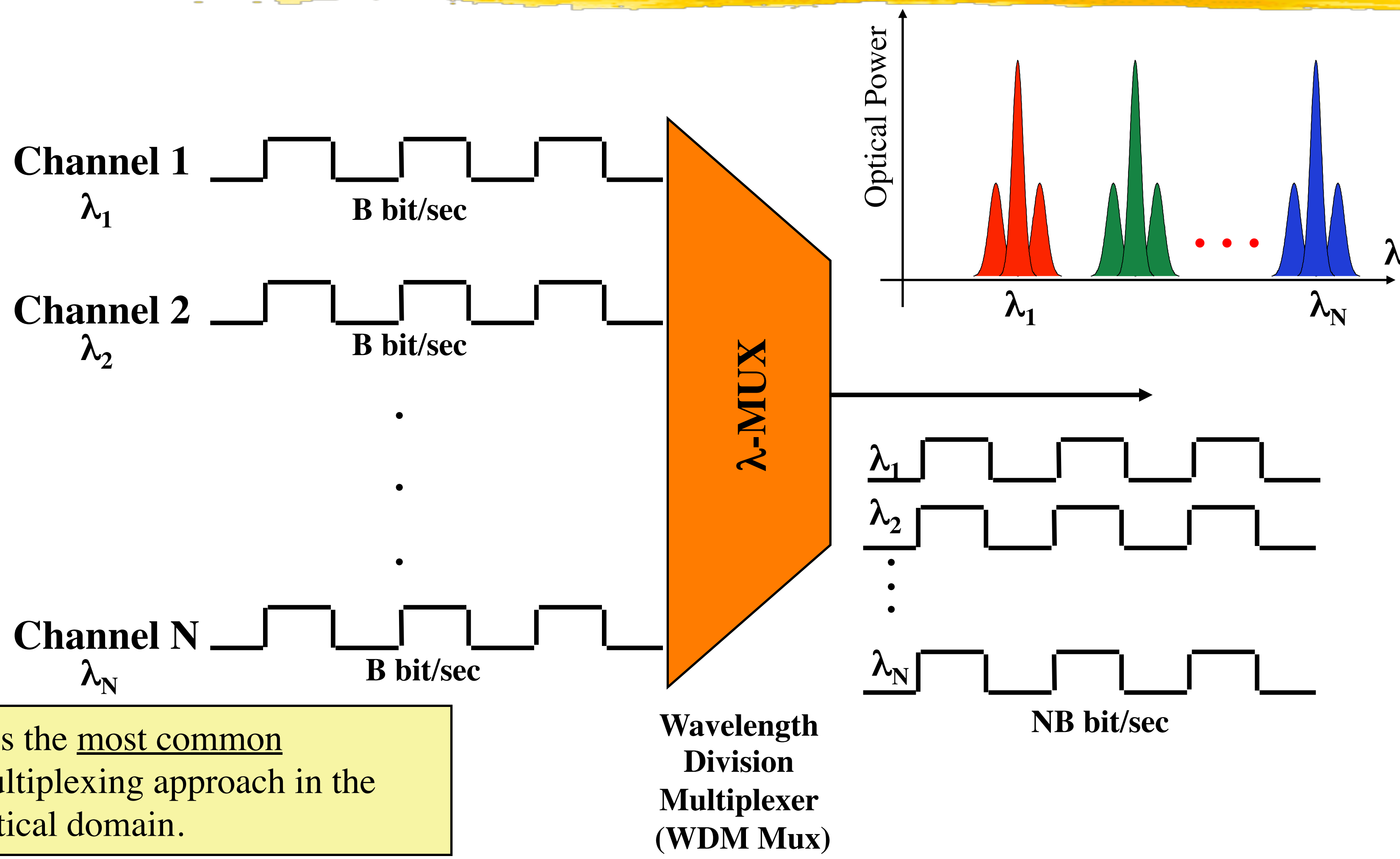
Time Division Multiplexing (TDM)



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

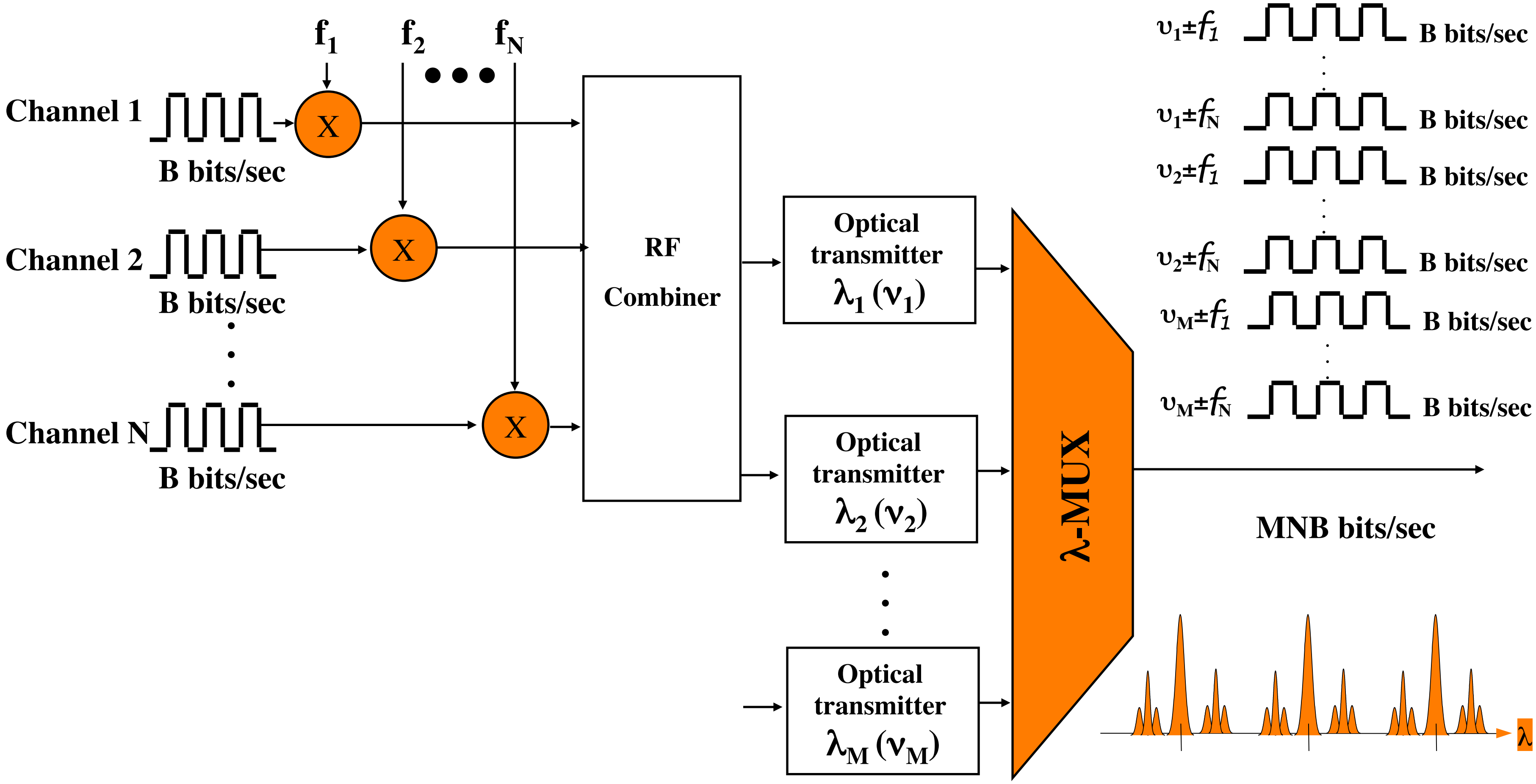
TDM is usually performed in the electronic domain, but is is now done also in the optical domain, for bit rates greater or equal to 40Gb/s

Wavelength Division Multiplexing (WDM)



It is the most common multiplexing approach in the optical domain.

Wavelength/Subcarrier Multiplexing



Optical Modulation

Modulation Basics (I)

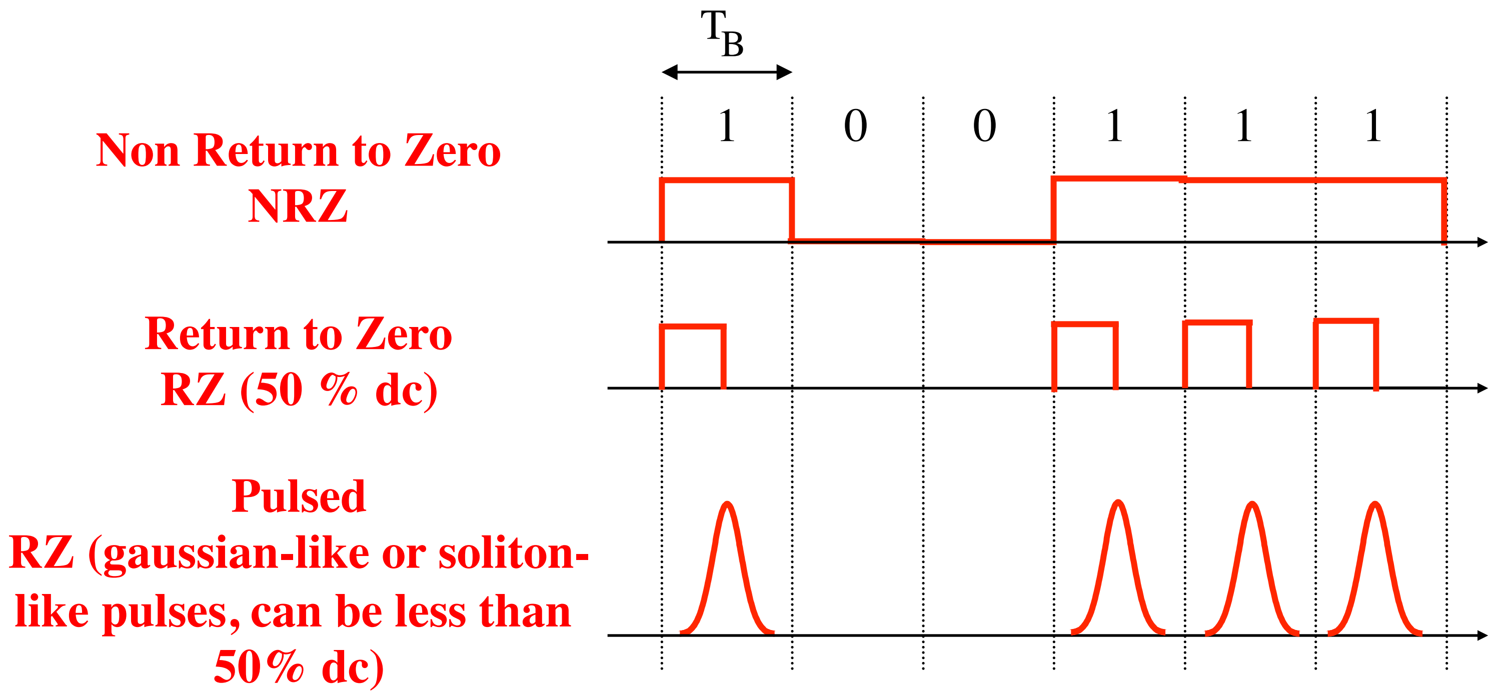
- Define
  - R_b = bit rate = bits/second
  - R_c = added redundancy per bit to improve SNR = baud = symbols/second
  - B = occupied bandwidth per channel
  - M = number of points in signal constellation
- Binary Modulation
  - One bit per symbol
- Non-Binary Modulation
  - More than one bit per symbol
- 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

$$R_b = R_s R_c \log_2 \mathrm{M}$$

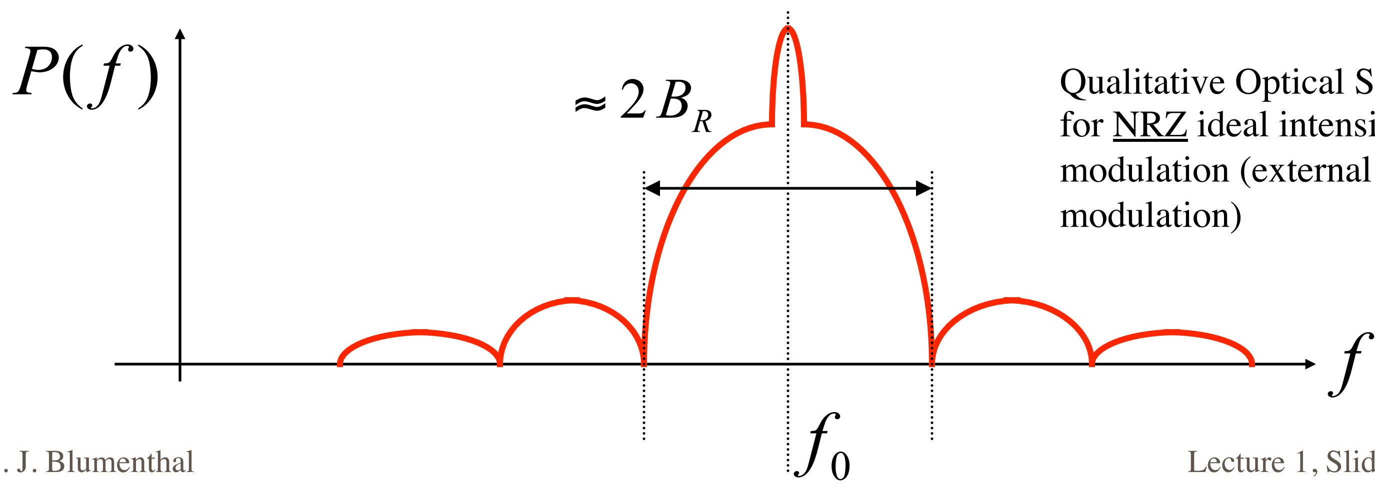
Binary Intensity Modulation

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



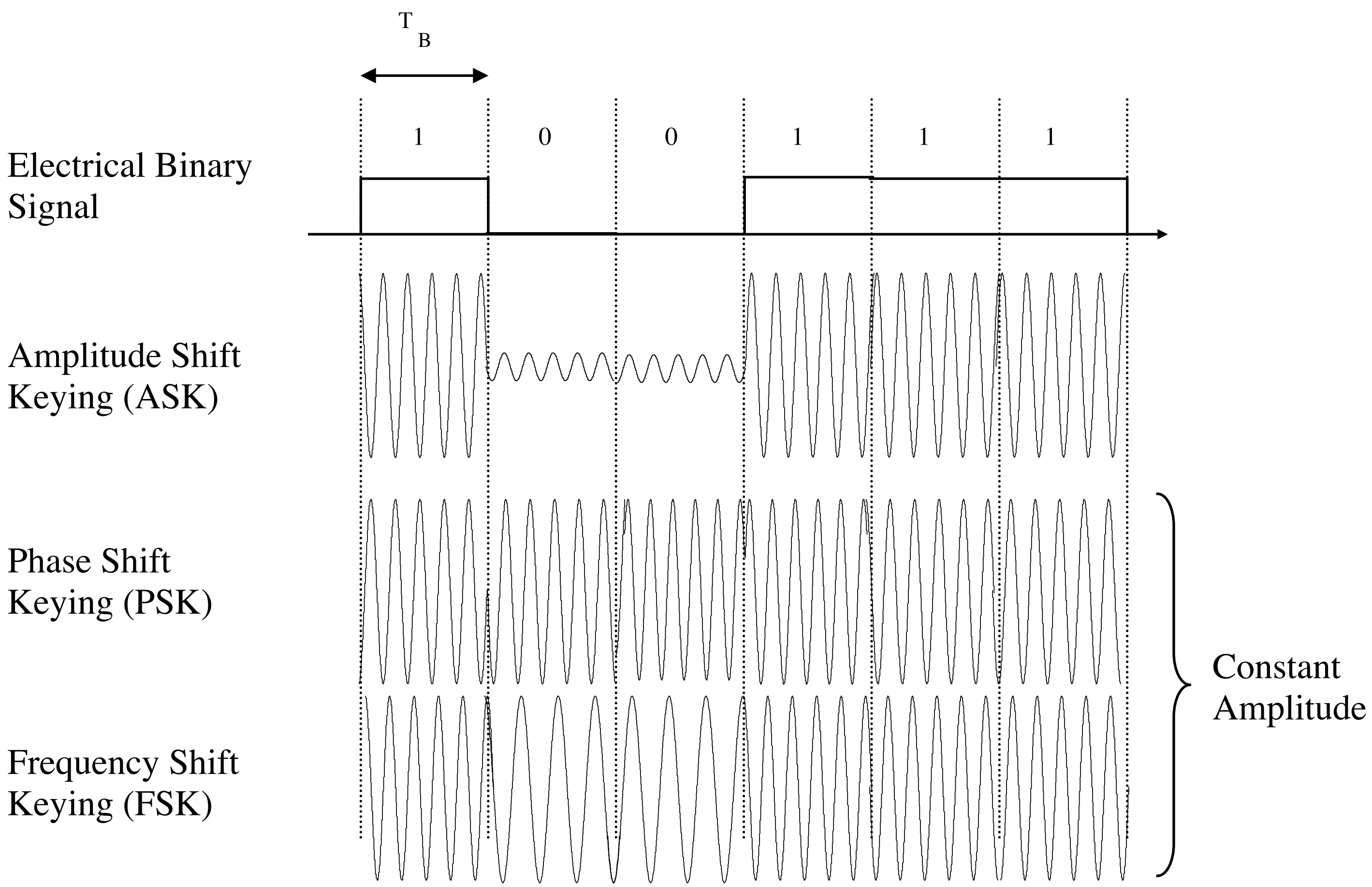
Optical spectrum for intensity modulation

- 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



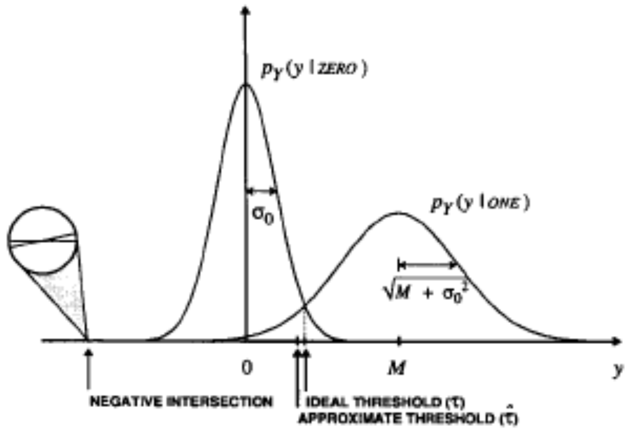
Qualitative Optical Spectrum for NRZ ideal intensity modulation (external modulation)

Coherent Binary Modulation

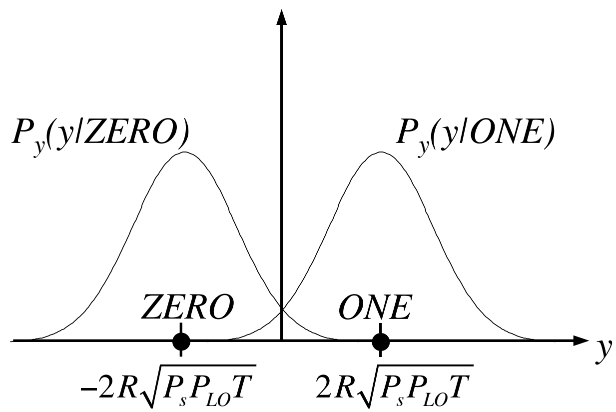


Binary Signal Constellations

Binary Intensity Modulation/Direct Detect
(IM/DD)



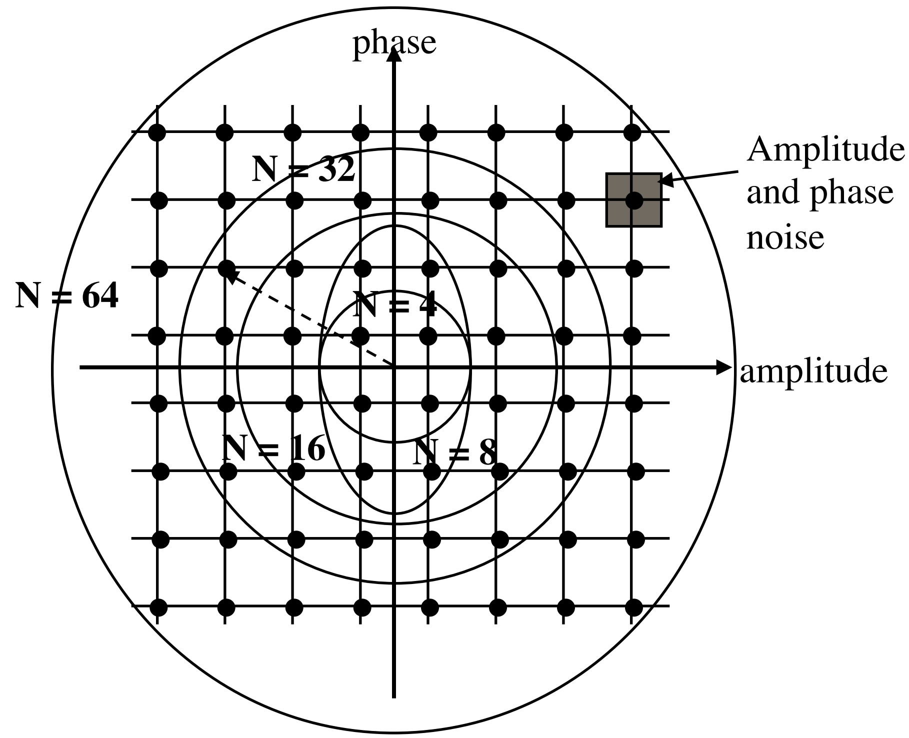
Two-Level PSK



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

Quadrature Multi-Level Modulation

- Both optical phase and amplitude can be used to code symbols per bit
- N-ASK is N-level amplitude shift keying (generalization of ASK): along amplitude axis
- N-PSK is N-level phase shift keying (PSK): along phase axis
- N-QAM is quadrature amplitude modulation: 2D in amplitude and phase
- Receiver must isolate one point in constellation per bit
- Noise makes more difficult to isolate symbol (SNR)
- 2-D space can be increased to 3 and 4-D by allowing temporal modulation of phase and amplitude



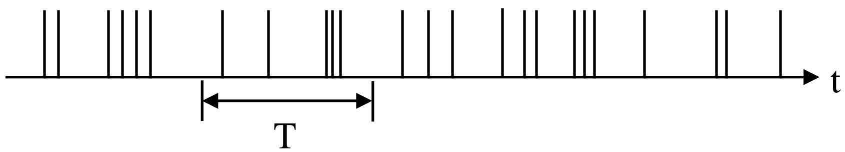
Photodetection

Detection of Optical Signals

- Thermal: Temperature change with photon absorption
  - Thermoelectric
  - Pyromagnetic
  - Pyroelectric
  - Liquid crystals
  - Bolometers
- Wave Interaction: Exchange energy between waves at different frequencies
  - Parametric down-conversion
  - Parametric up-conversion
  - Parametric amplification
- Photon Effects: Generation of photocarriers from photon absorption
  - Photoconductors
  - Photoemissive
  - Photovoltaics

Photon Statistics

- Photon sources can in general be characterized as coherent or incoherent†
  - Coherent: Probability that a photon is generated at time t_0 is mutually independent of probability of photons generated at other times (Markov Process)
    - Poisson Process: Probability of finding n photons in time interval T
      - Bunching is a trait of the Poisson process
      - Interarrival time is decaying exponentially distributed



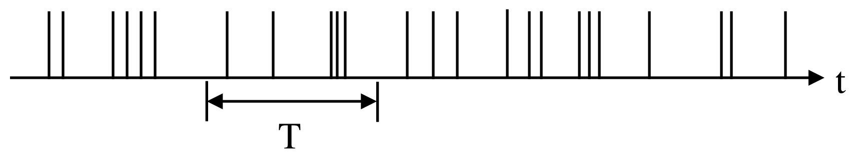
$$P(n \mid T) = \frac{(rT)^n e^{-rT}}{n!}$$

† Can also be a combination of these two types -> partially coherent

Where :
P(n|T) is probability of finding n photons in time interval T
R is mean photon arrival rate (photons/second)

Photon Statistics (II)

- Narrowband Thermal (Gaussian):
  - Bose-Einstein Process: Probability of finding *n* photons in time interval *T*



$$P(n) = \left(\frac{1}{1+n_b}\right)\left(\frac{n_b}{1+n_b}\right)^n$$

Where :

P(n) = probability of finding n photons given

n_b = mean number photons from incoherent source = $N_0/h\nu_0$

N_0 = spectral density of source = P_{opt}/B_0

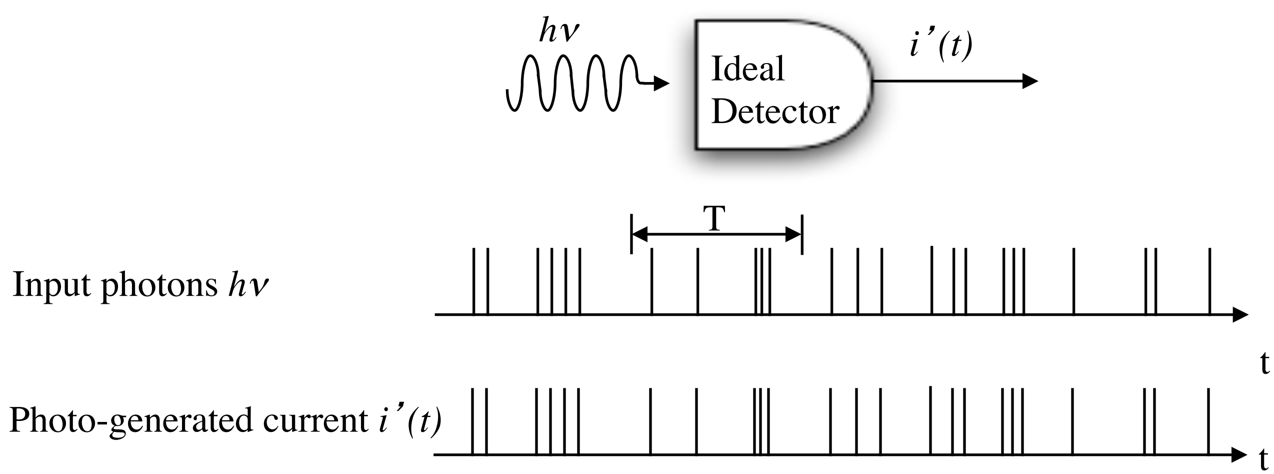
P_{opt} = total optical power from source

B_0 = source optical bandwidth

T = observation time ≤ $1/B_0$

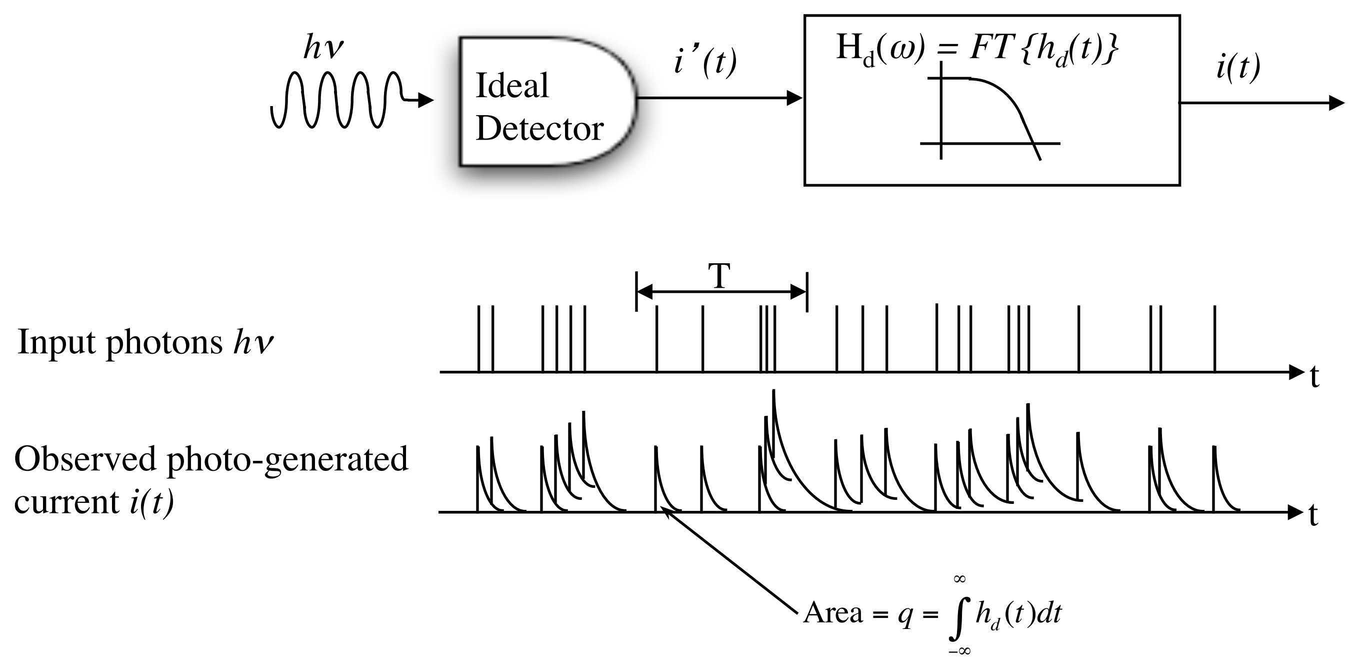
Detecting Photons (1)

- Any material that can respond to single photons can be used to count photons
- Ideal Detector
  - Generation of a electron-hole pair per absorbed photon results in an instantaneous current pulse



Detecting Photons (2)

- Real Detector
  - Has an inherent "impulse response," $h_d(t)$, due to built in resistance and/or capacitance.
  - Can be modeled as an RC filter with low pass response



Detecting Photons (3)

- As the average photon rate increases, the observed photo-current starts smoothing out, with a variance around the mean (average) count that is based on the statistics (which tends to Gaussian for large photon arrival rate)
- *P(i)* is the probability function of measuring the current at a certain value at time t.