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

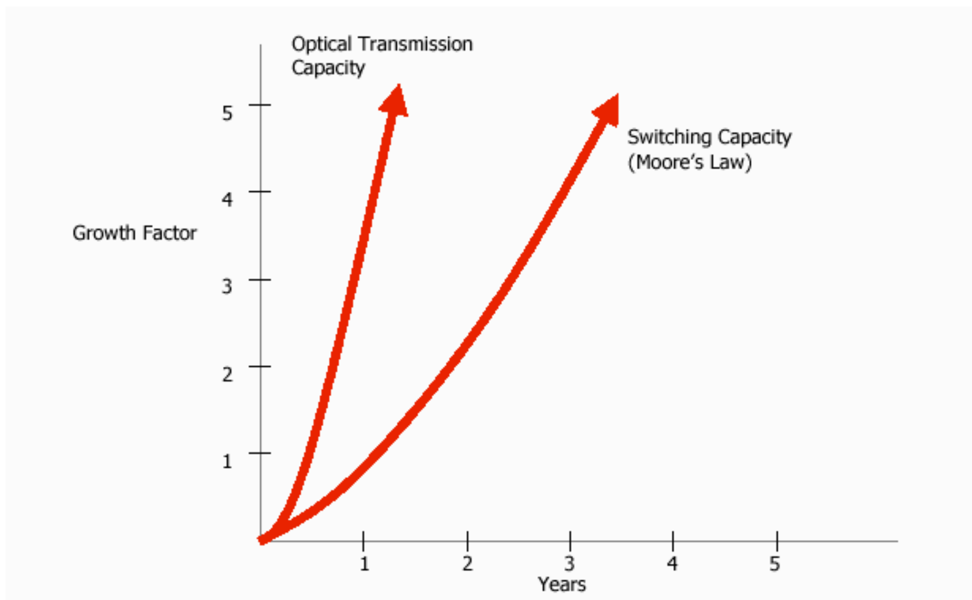
Overview of Optical Communications Links

Fiber-Optic Network Applications

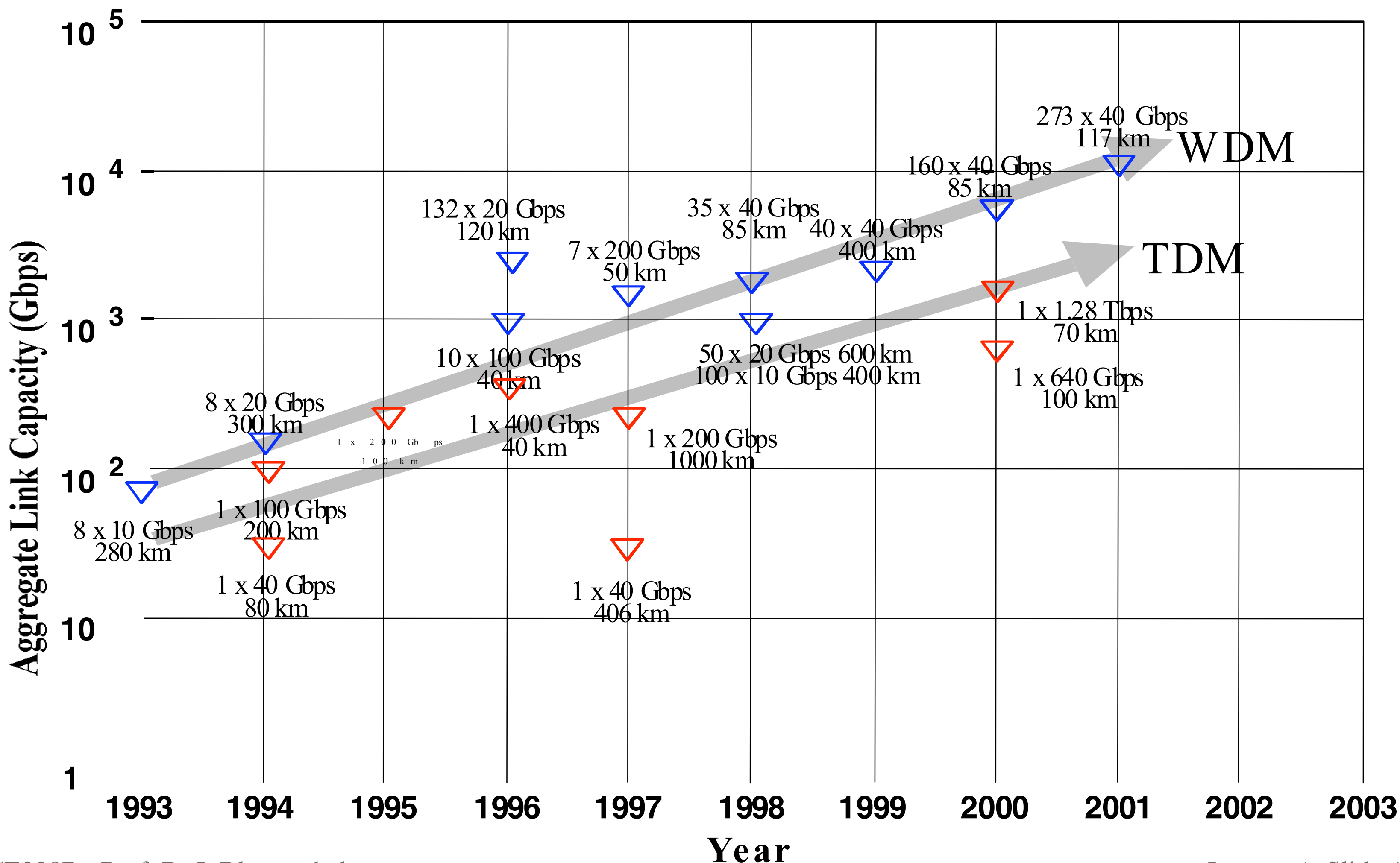
- Main application: digital transmission
  - Voice, telephone
  - Data
    - IP Networks
    - ATM, Gigabit Ethernet, FDDI, etc.
    - Distributed Computing and Databases
    - Video, Multimedia
- Microwave Photonics
  - Fiber/Wireless
  - Hybrid Fiber/Coax
- Other applications
  - Fiber/Wireless
  -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

Note:

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



Transmission Bandwidth Evolution



Evolution of Fiber-Optic Point-to-Point Transmission

Early 70s

Multimode fiber-optic waveguides >5dB/km attenuation

Room temperature GaAs LEDs and multimode FP Lasers @ 830 nm

Early 80s

Low loss Single mode optical fibers 1 dB/km @ 1310 nm

Multimode Fabry-Perot 1310 nm lasers

Mid to Late 80s

Operation in the low loss window of 0.2 dB/km @ 1550 nm but high dispersion @ 1550 nm

Development of single frequency DFB 1310 nm and 1550 nm lasers

New dispersion shifted fiber yields Zero dispersion @ 1550 nm and 0.5 dB/km loss @ 1310 nm

Late 80s to Early 90s

Multichannel erbium doped fiber amplifiers (EDFAs) @ 1550 nm deployed.

Mid 90s

Multichannel WDM @1550 nm. Number of channels and channel spacing limited by fiber four-wave mixing (FWM)

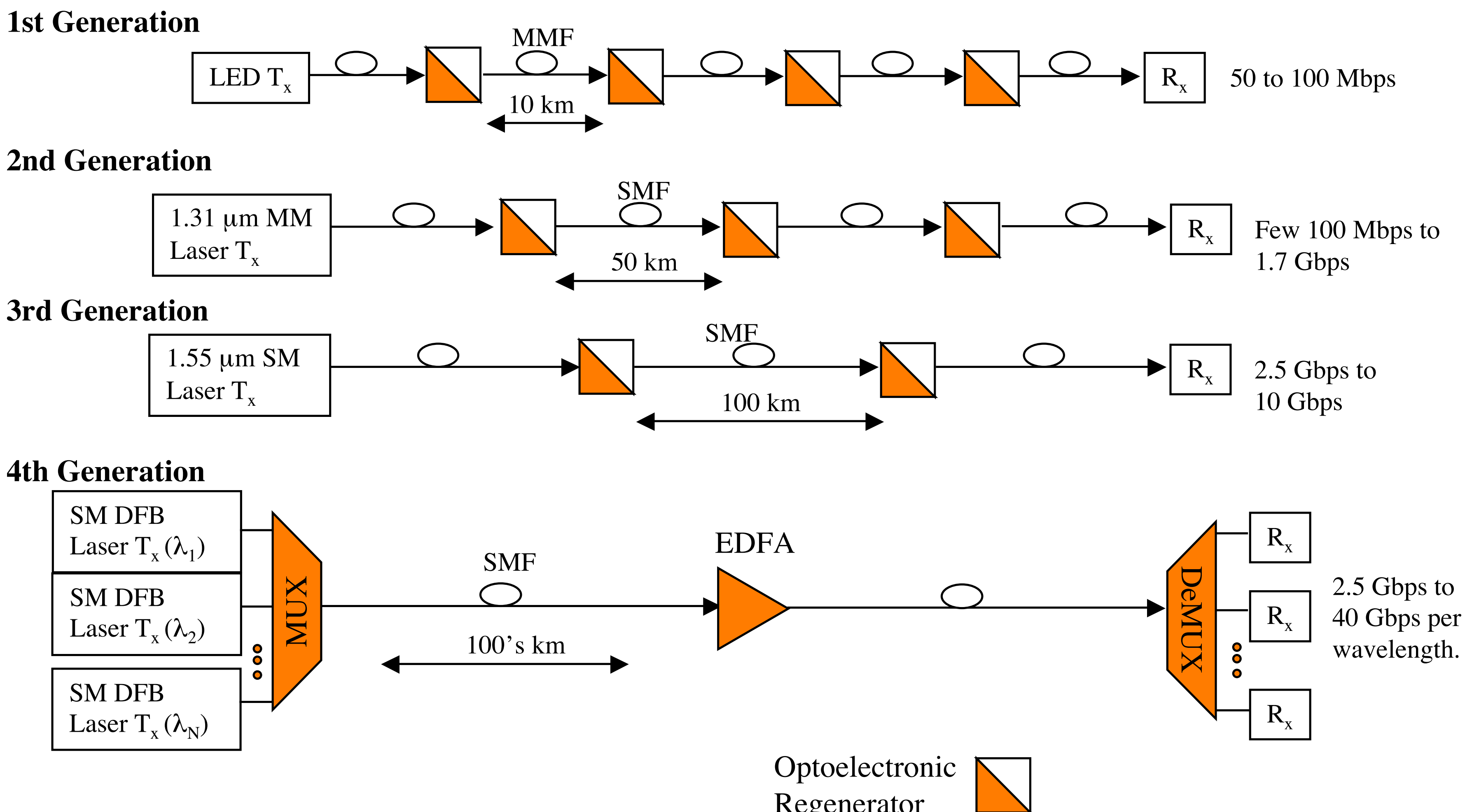
AT&T True Wave Fiber and Corning Large Optical Core Fiber reduce fiber FWM

Mid 90s

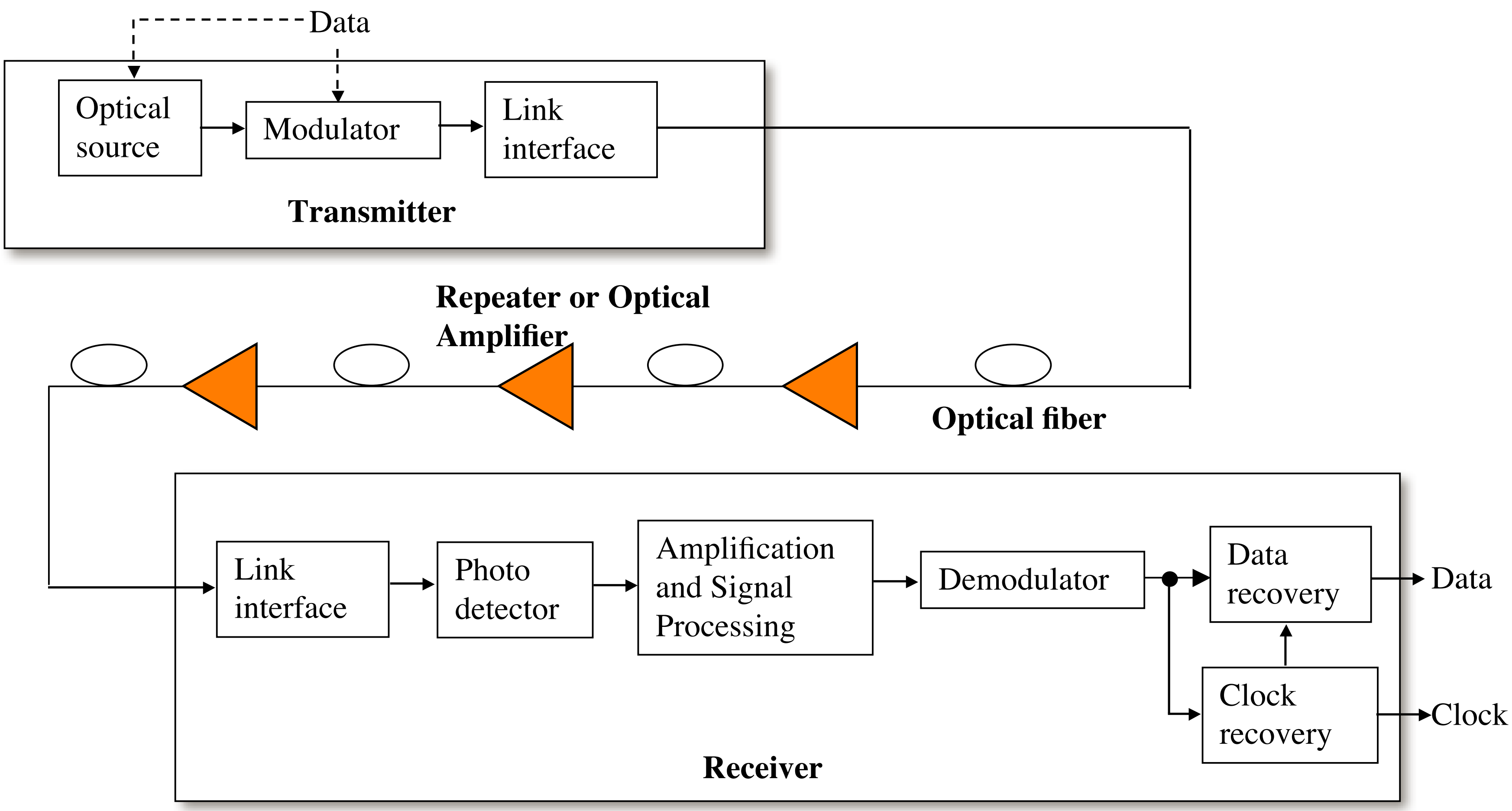
Optical Solitons, dispersion compensation

1st Generation | **2nd Generation** | **3rd Generation** | **4th Generation** | **5th Generation**

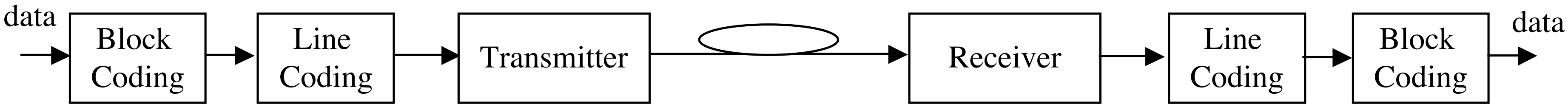
DWDM Link Evolution



Basic Fiber Optic Point-to-Point Link



Basic Communication System



<u>Block Coding</u>
- •Error Correction
- •Redundancy
- •Overcome noise and transmission impairments
- •E.g. FEC, Turbo-Codes

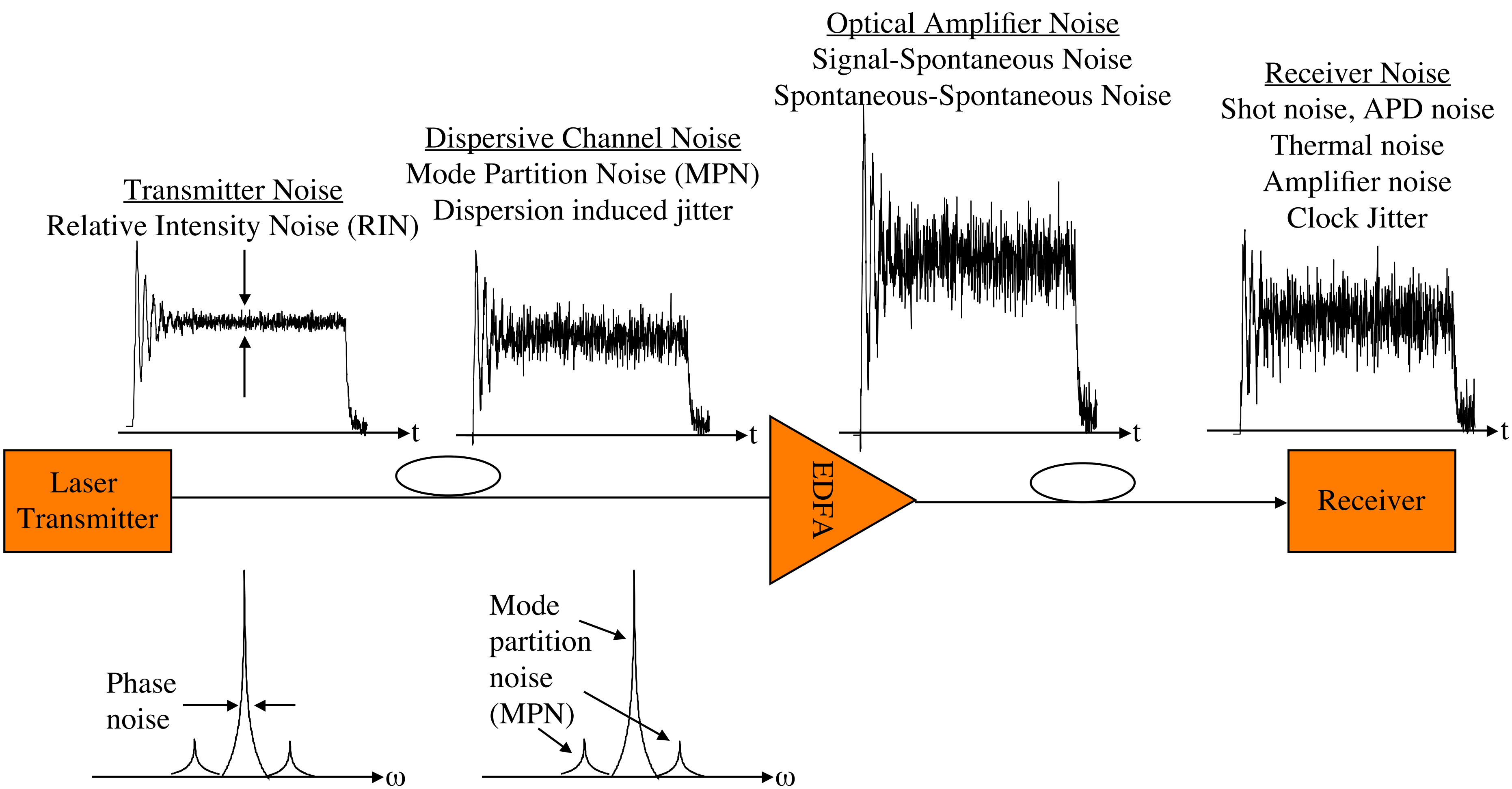
<u>Line Coding</u>
- •DC balance
- •Redundancy
- •E.g Manchester Codes

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)

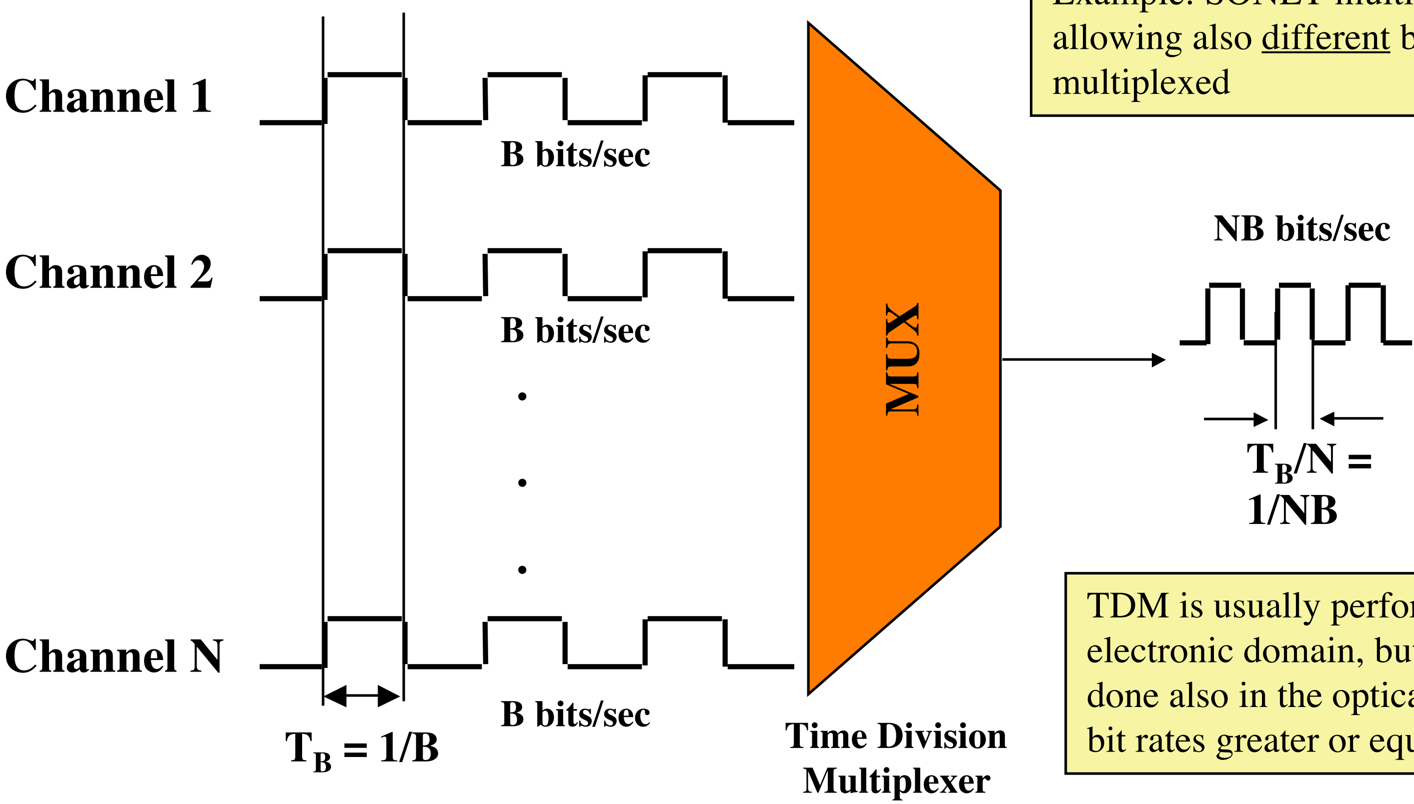


Multiplexing Techniques

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

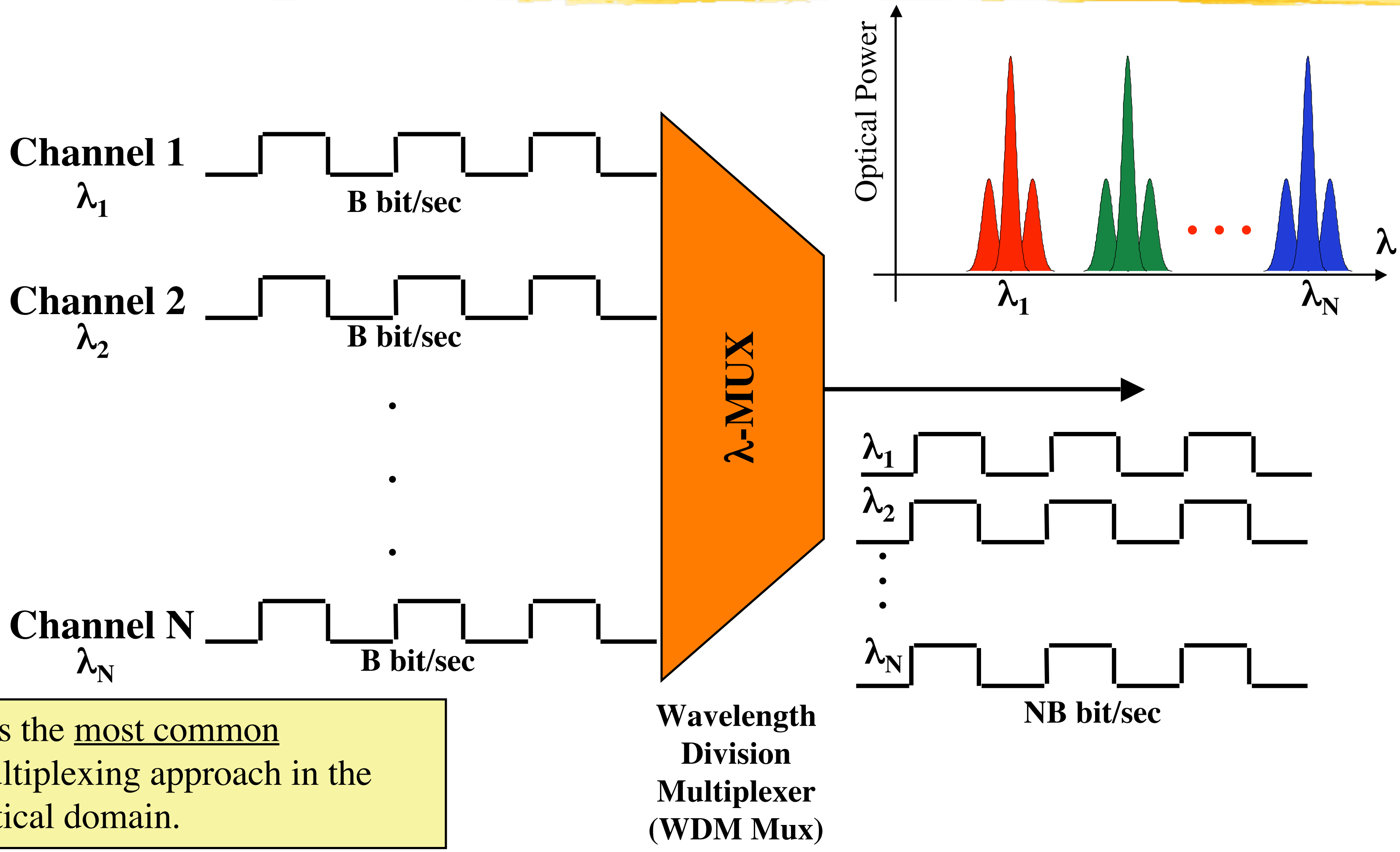
Time Division Multiplexing (TDM)



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

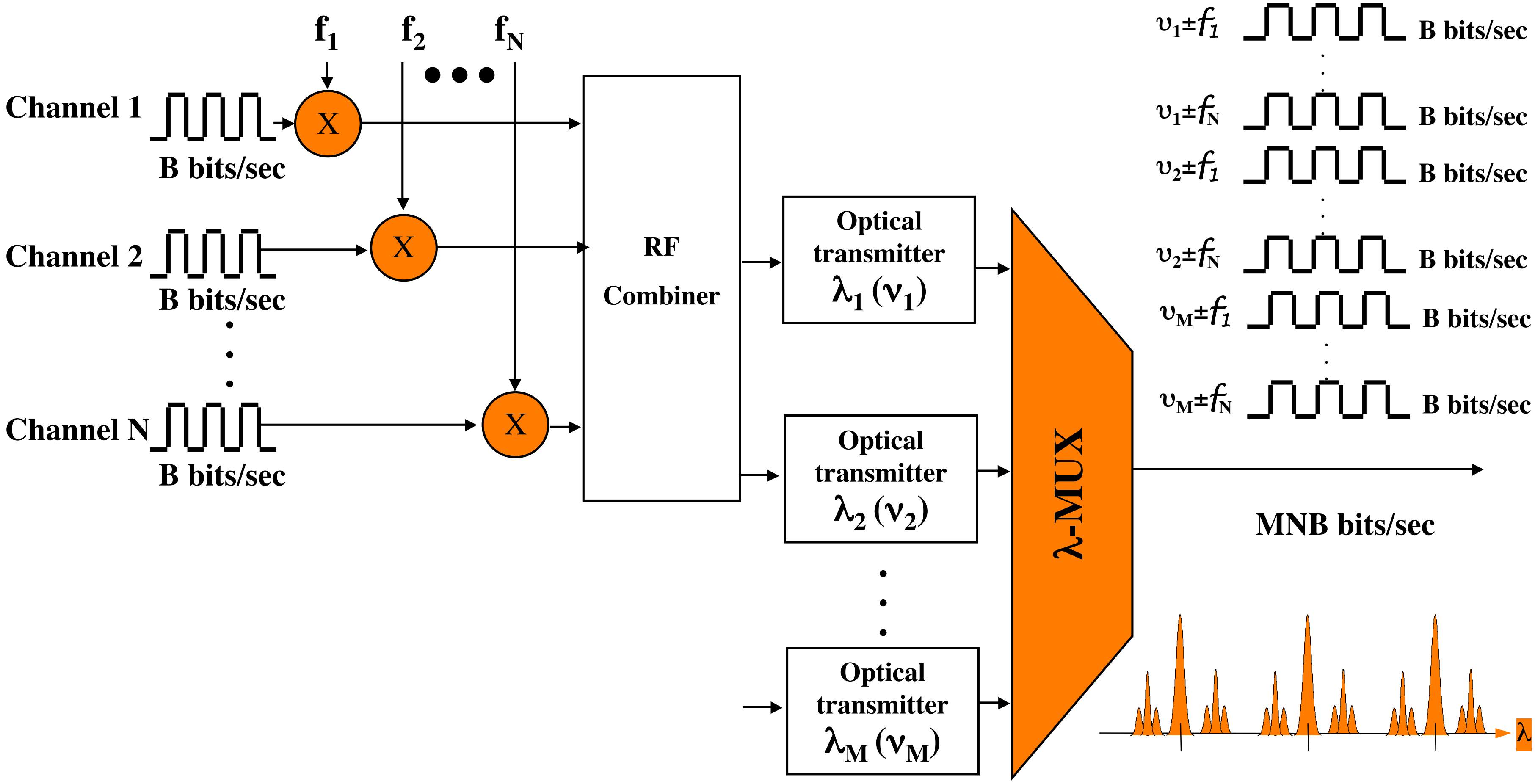
TDM is usually performed in the electronic domain, but is is now done also in the optical domain, for bit rates greater or equal to 40Gb/s

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

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

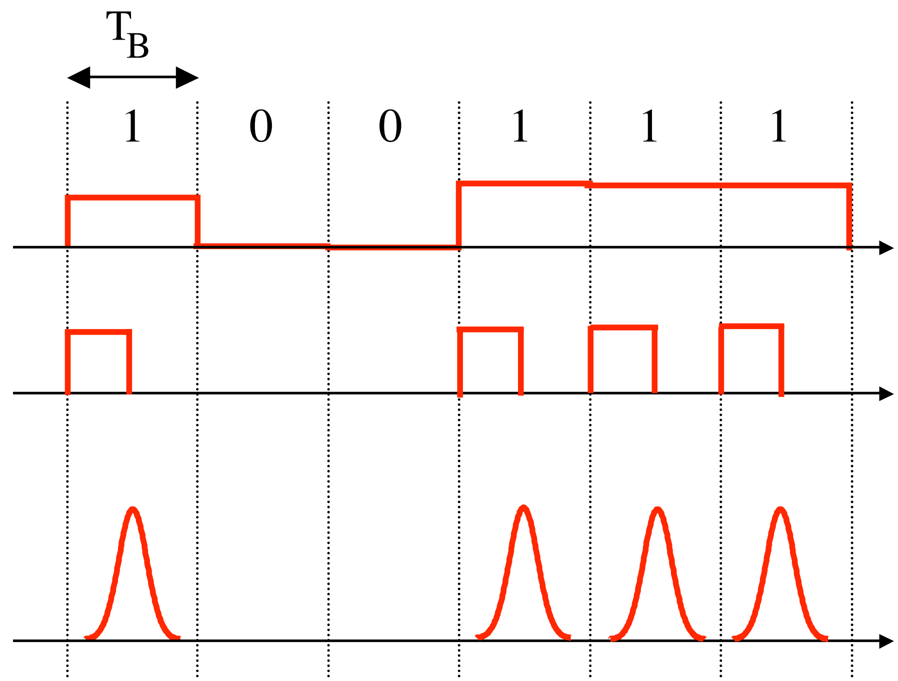
Binary Intensity Modulation

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

Non Return to Zero
NRZ

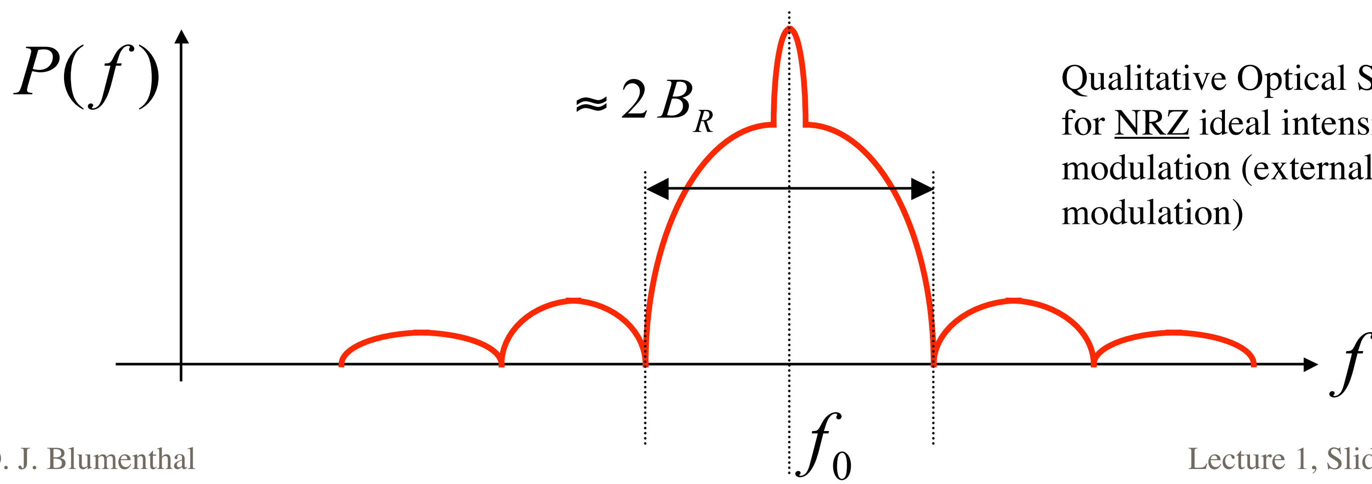
Return to Zero
RZ (50 % dc)

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



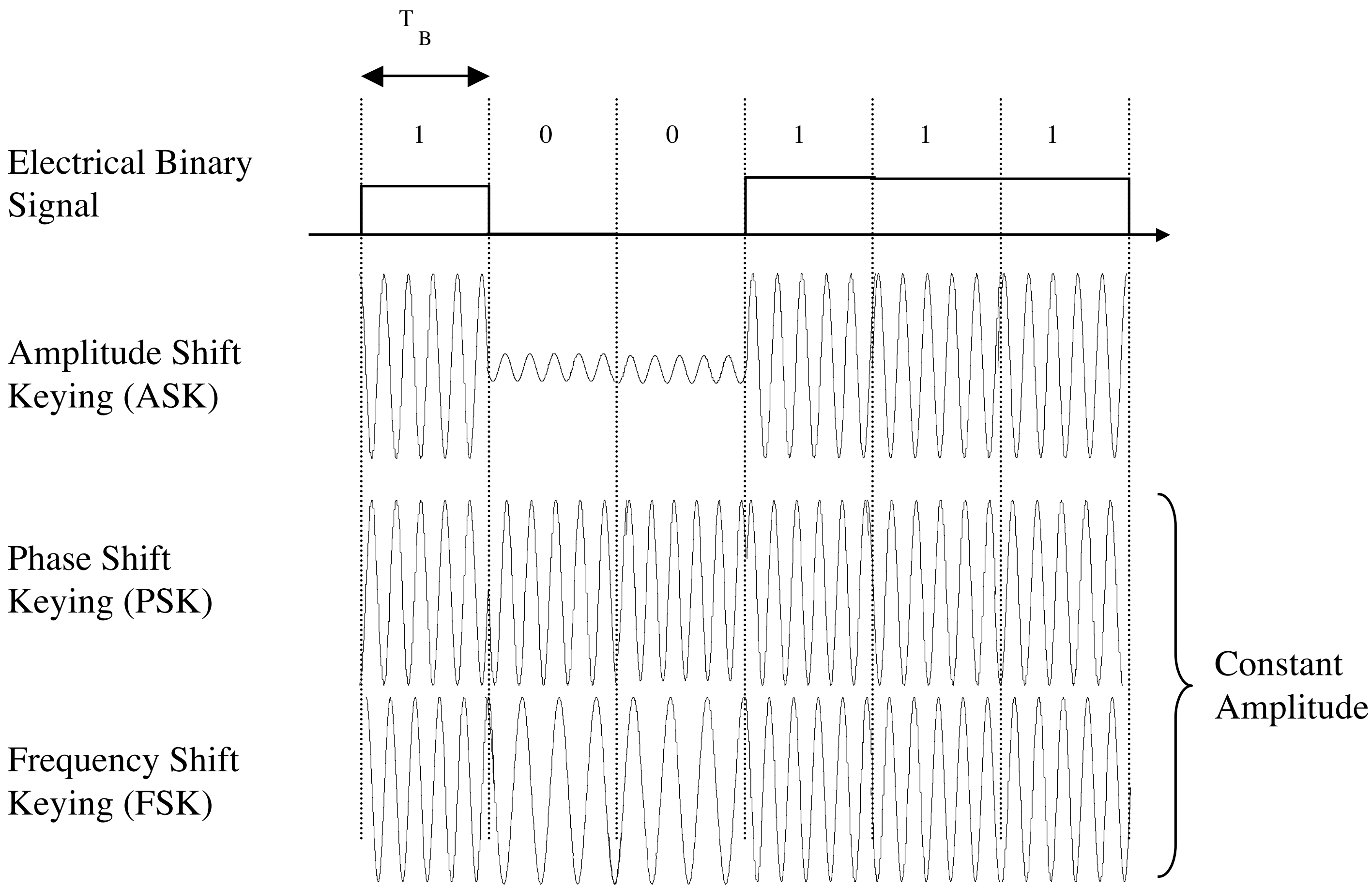
Optical spectrum for intensity modulation

- 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



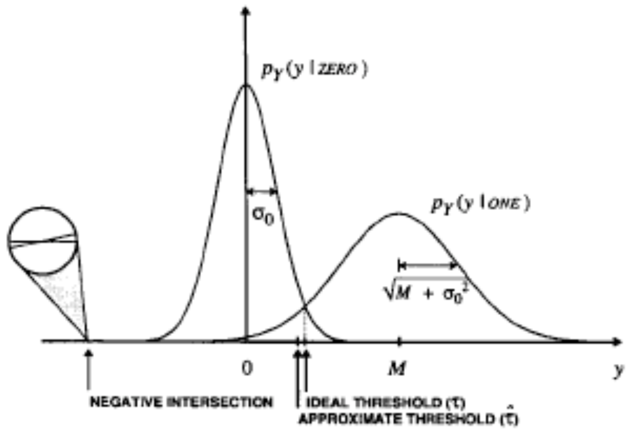
Qualitative Optical Spectrum for NRZ ideal intensity modulation (external modulation)

Coherent Binary Modulation

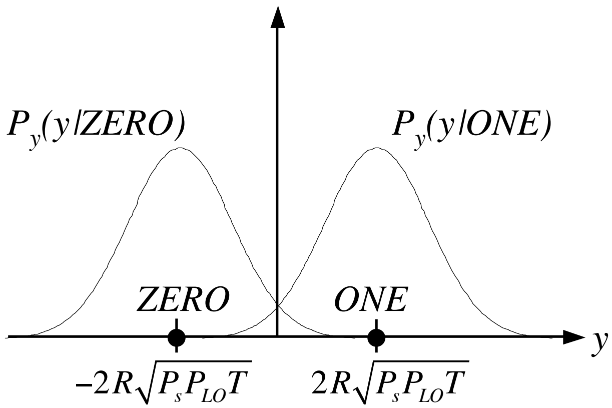


Binary Signal Constellations

Binary Intensity Modulation/Direct Detect
(IM/DD)



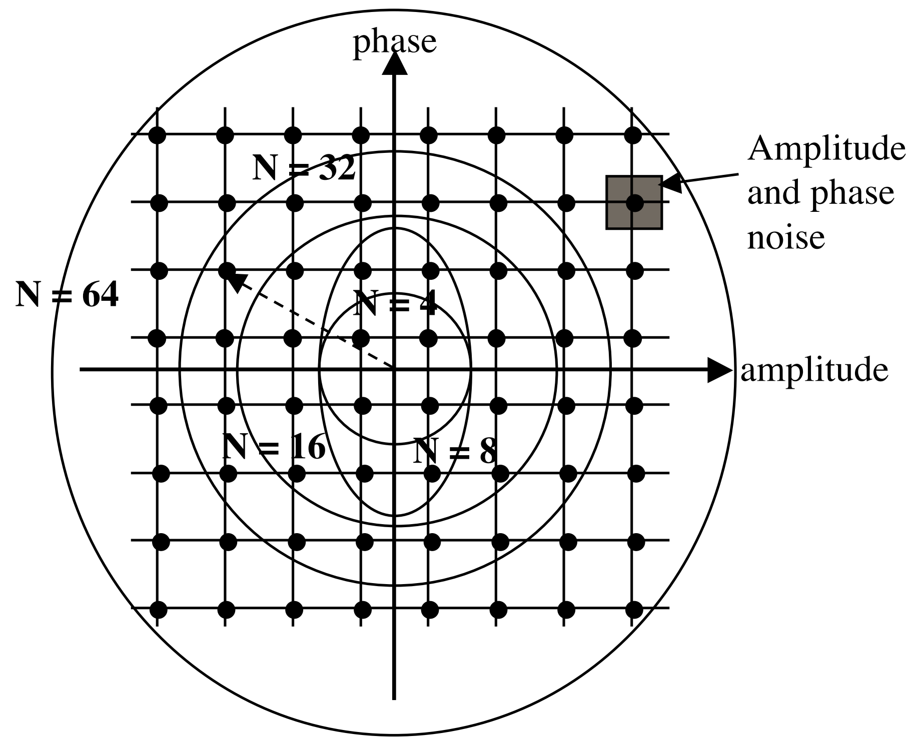
Two-Level PSK



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

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



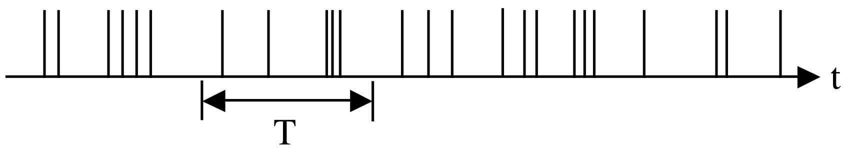
Photodetection

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



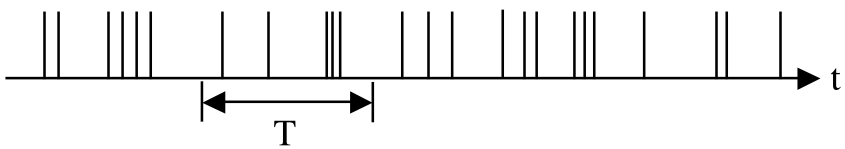
$$P(n|T) = \frac{(rT)^n e^{-rT}}{n!}$$

† 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*

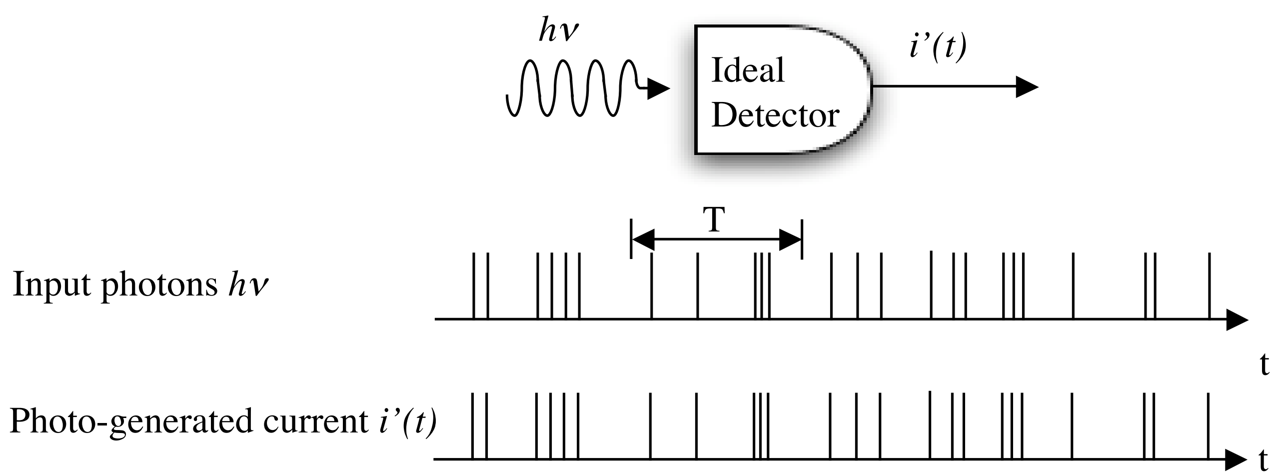


$$P(n) = \left(\frac{1}{1+n_b}\right)\left(\frac{n_b}{1+n_b}\right)^n$$

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 ≤ $1/B_0$

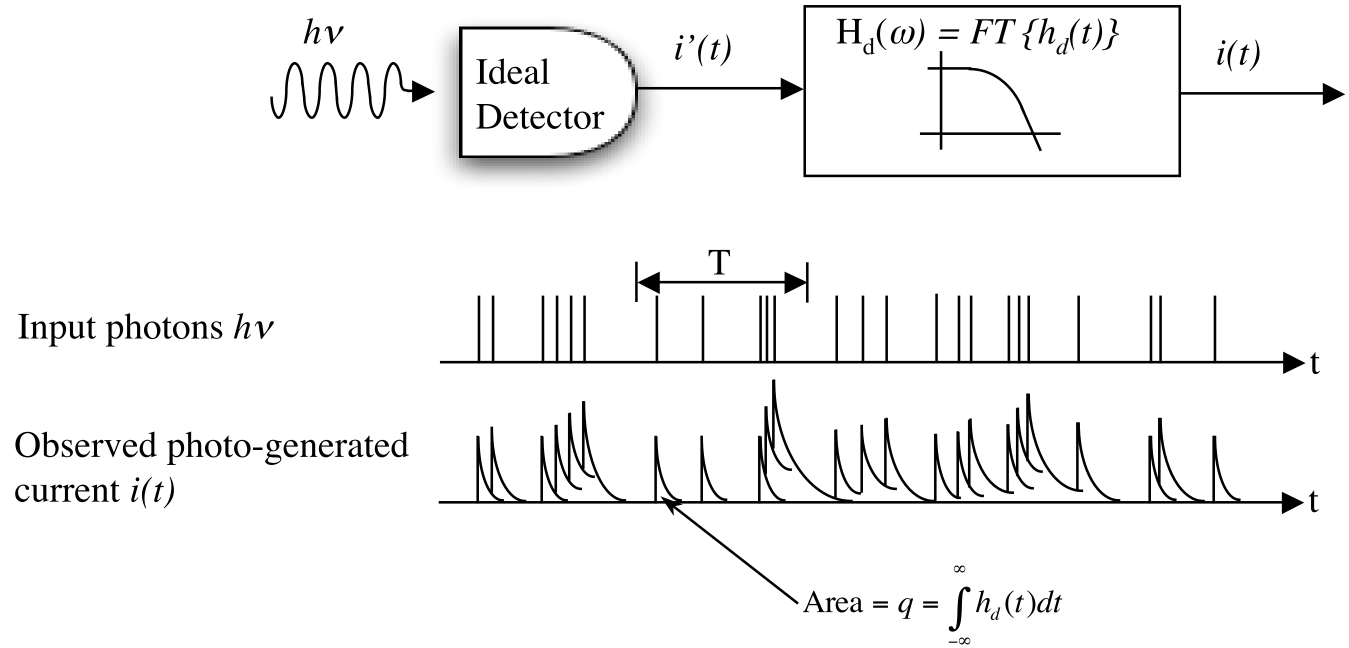
Detecting Photons (1)

- 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



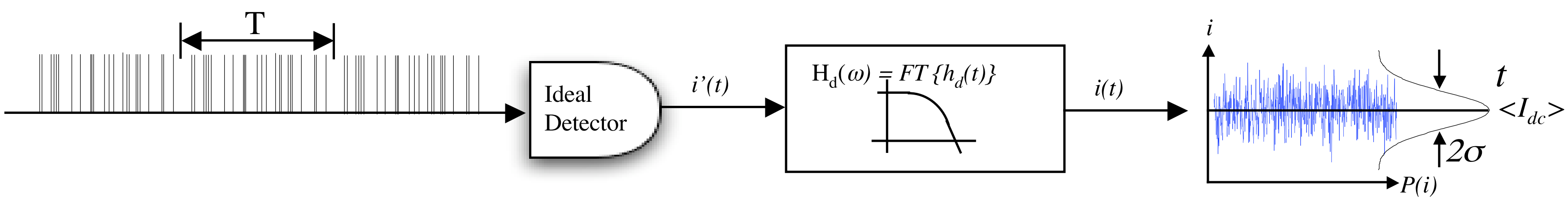
Detecting Photons (2)

- 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.



Detecting Photons (4)

- The detector output current *i(t)* can be modeled as a discrete "filtered Poisson" process

$$i(t) = \sum_{j=1}^{N} h_d(t - \tau_j)$$

  - Where $h_d(t)$ is PD impulse response, N is total number e-h pairs generated, τ_j is the random time the j^{th} photocarrier is generated.

- Define: Quantum Efficiency (QE), unitless, as

$$\eta = \frac{\text{number of photocarriers produced}}{\text{number of incident photons}}, \; 0 \leq \eta \leq 1$$

- Define: Time varying photon rate parameter ($\lambda(t)$) in units of photocarriers/second as

$$\lambda(t) = \frac{\eta}{h\upsilon} P_{recvd}(t)$$

Detecting Photons (5)

- The power incident on a photodetector of area A, in units of Watts, is

$$P(t) = \int_A I(\vec{p},t)\,dA$$

  - where the instantaneous optical intensity at an observation point $\vec{p}$ is given by

$$I(\vec{p},t) = \frac{1}{Z_0}\left|E(\vec{p},t)\right|^2$$

- The time varying photon rate parameter $\lambda(t)$ can then be written in terms of $P(t)$

$$\lambda(t) = \frac{\eta}{h\nu}\frac{\left|E(t)\right|^2}{Z_0}$$

Detecting Photons (6)

- If we consider an observation interval, over which we are going to average our photon count over
  - This can be due either to the inherent bandwidth of the detector or (as we will see later) on purpose to match the receiver bandwidth to the data bit rate
- Then the number of photocarriers generated over the interval T counted at the j^{th} observation interval

$$N_j = \int_0^T \lambda_j(\tau)\,d\tau$$

- Assuming a coherent source, the ***conditional inhomogeneous Poisson process*** describes this photon count during the j^{th} observation interval

$$P(N_j = N) = \frac{\left(\int_0^T \lambda_j(\tau)\,d\tau\right)^N}{N!} e^{\left(-\int_0^T \lambda_j(\tau)\,d\tau\right)}$$

Detecting Photons (7)

- If we assume a constant rate parameter over the time interval T (independent of *j*), then the photo-generated current can be written as

$$i(t) = \lambda(t) q$$

$$\lambda(t) = \frac{N}{T}$$

- Then the photocurrent produced by the photodetector can be written in Amperes, assuming the observation time is normalized to one second

$$i(t) = \lambda(t) q = \frac{\eta q}{h\nu} P_{rcvd}(t)$$
$$= \Re P_{rcvd}(t)$$

  - Where we have defined the detector responsivity as

$$\Re = \frac{\eta q}{h\nu}$$