Lecture 16: Advance Topics

Fiber Transmission Link Design

Design Considerations

- Total link length
- Repeater spacing
- Wavelength plan and Number of WDM Channels
- Maximum bit rate per WDM channel
- Performance and bit error rate (BER)
- Link cost
- Environmental conditions
- Reliability and failure rate
- Link upgrade

<u>Note on upgradability</u>:
Optical transmission systems have an enormous potential capacity
Carrier often which to buy DWDM systems that can be upgraded to a very large number of channels, but the may want to ligth only a few wavelengths at the beginning of operation

Link Design Issues

- Power Budget
- Rise Time Budget
- Dispersion management (Chromatic and PMD)
- Fiber Nonlinearities
- Optical Crosstalk
- Receiver sensitivity
- Power penalties

Wavelength Plan

- Interchannel Spacing
  - Large wavelength spacing
    - Reduces requirements on components
    - Allows future upgrade to higher bit rates
  - Smaller channel spacing
    - Allows more channels to be packed within amplifier gain bandwidth
- Wavelength Planning
  - ITU standardization of wavelength position and channel spacing

- Ex. 100 GHZ=0.8 nm @ 1550 nm
  - EDFA BW 1530 nm - 1564 nm
  - Allows approximately 43 channels

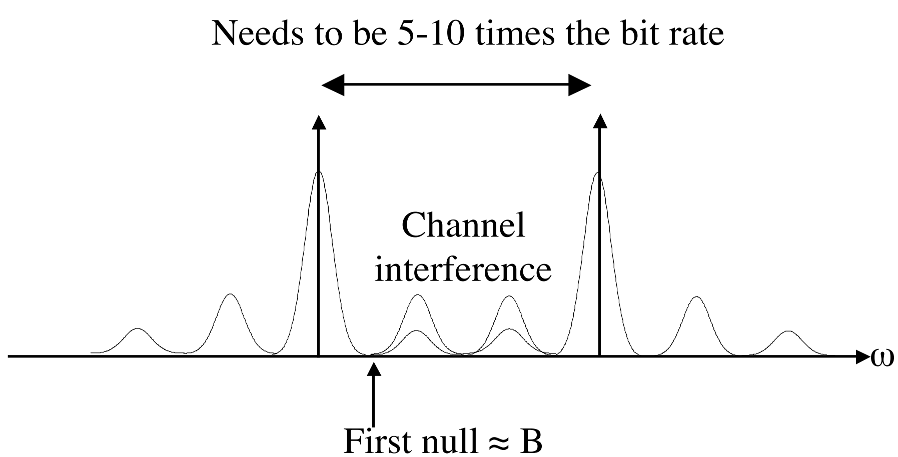
ITU-T Recommendation G.692

ITU-T Recommendation G.692

- This recommendation sets the worldwide standard for wavelength allocation
  - It uses absolute frequency (and not wavelength)
- The ITU grid is centered at 193.1 THz (1552.52 nm)
  - The generation of an absolute frequency reference (AFR) is still an open issue
- The basic channel spacing is 100 GHz
  - The recommendation already envisioned 50 and 25 GHz channel spacing, which are now becoming a reality
- The recommendation considered only the so-called C-band (1530 - 1565 nm)
  - Other band are available today:
    - L-Band: 1565 nm - 1620 nm
    - S-Band: 1485 nm -1525 nm

Wavelength Channel Separation

- The current ITU grid is reference to 100 GHz channel spacing. However, there is significant effort to build systems that operate with 50, 25 and 10 GHz channel spacing as filter technology improves.
- The limit on channel spacing, given that the laser and filter technology can meet the requirements, comes down to the modulation bit rate.
- A general rule of thumb is that the wavelength channel spacing needs to be a minimum of 5-10 time the channel bit rate.

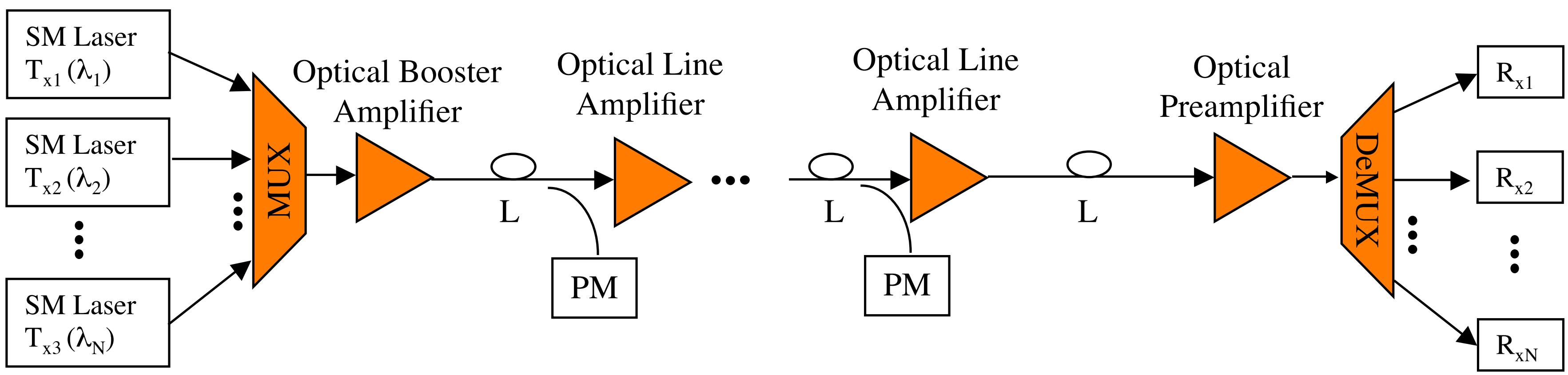


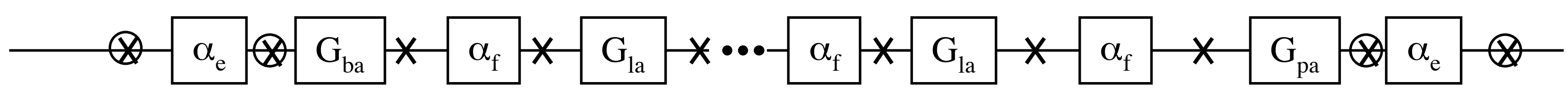
Wavelength Registration

32 Channels of the ITU Wavelength Grid (referenced to vacuum)

Channel	Wavelength	Channel	Wavelength
1	1557.36	17	1544.53
2	1556.55	18	1543.73
3	1555.75	19	1542.94
4	1554.94	20	1542.14
5	1554.13	21	1541.35
6	1553.33	22	1540.56
7	1552.52	23	1539.77
8	1551.72	24	1538.98
9	1550.92	25	1538.19
10	1550.12	26	1537.40
11	1549.31	27	1536.61
12	1548.51	28	1535.82
13	1547.72	29	1535.04
14	1546.92	30	1534.25
15	1546.12	31	1533.47
16	1545.32	32	1532.68

WDM Link Power Budget

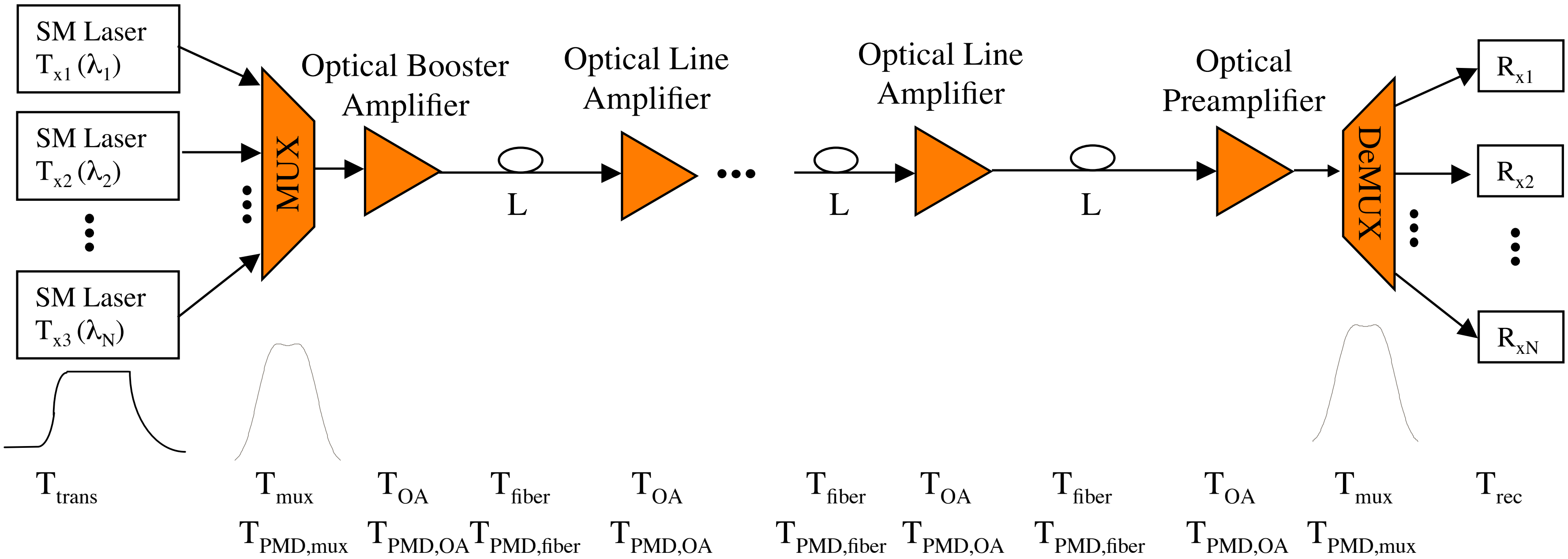




⊗ Connector
X Splice
PM Power Monitor

$$P_{rec} = P_{trans} - \alpha_{fiber} L_{total} - N_{conn}\alpha_{conn} - N_{splice}\alpha_{splice} - N_{PM}\alpha_{PM} - \sum \alpha_{excess} - \sum \alpha_{PDL} + \sum G_{OA} - \sum PP - M_{System}$$

Rise Time Budget



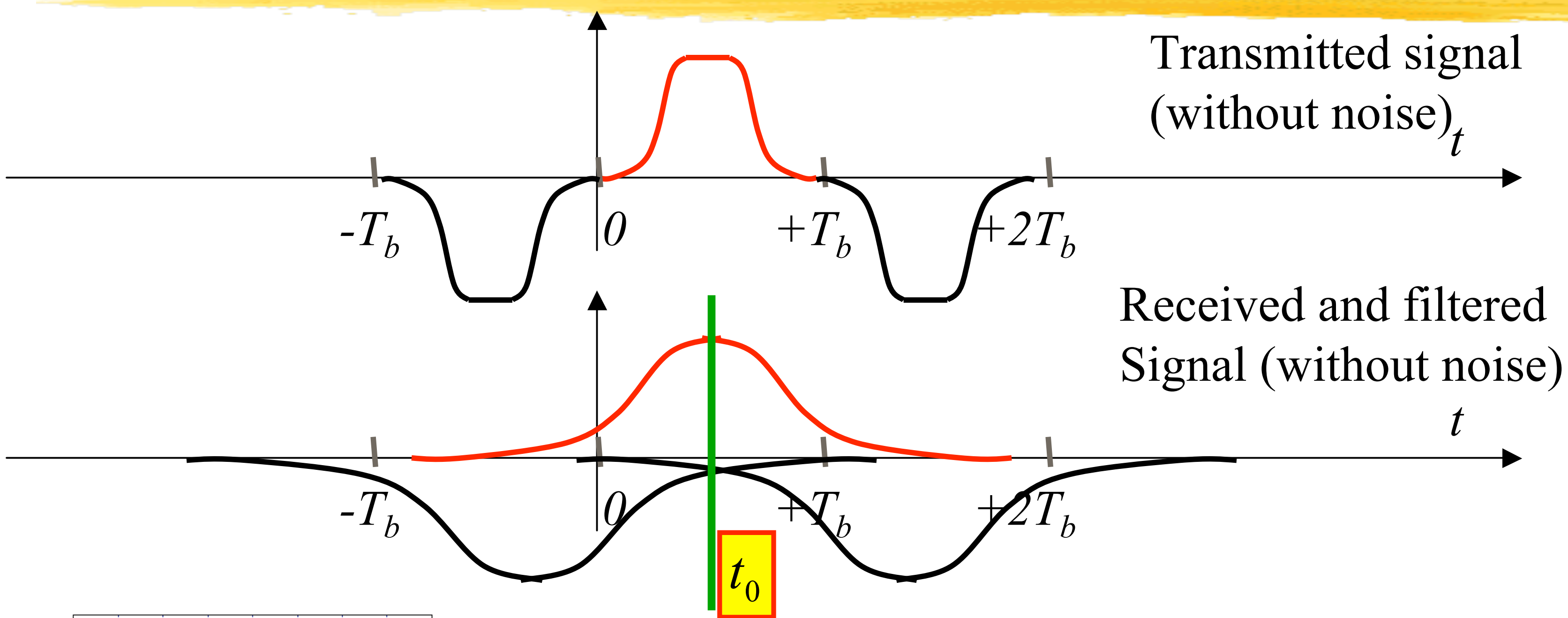
$$T_{r,sys} = \sqrt{T_{Trans}^2 + T_{filter,equiv}^2 + T_{fiber}^2 + \sum T_{PMD}^2 + T_{rec}^2}$$

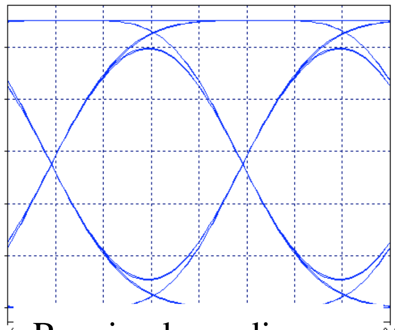
$$T_{fiber}^2 \approx T_{GVD}^2$$

Example required system rise-time

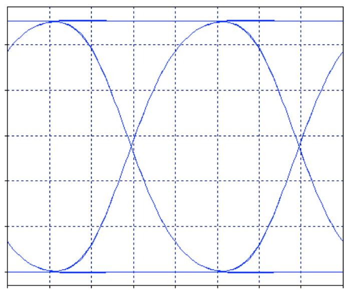
$$T_{r,sys} \le \begin{cases} 0.35/B, & \text{for RZ} \\ 0.70/B, & \text{for NRZ} \end{cases}$$

ISI: Inter Symbol Interference





Received eye diagram with significant ISI

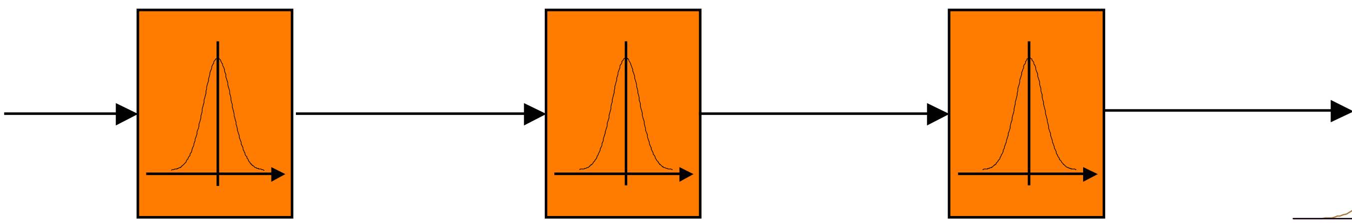


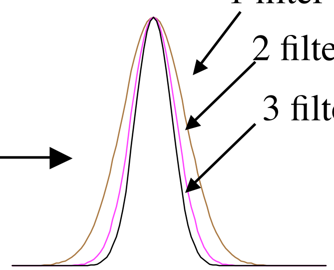
Received eye diagram without ISI

Cascaded frequency selective components

- Leads to power penalty due to filter misalignment
- Leads to reduced risetime due to filter narrowing

Bandwidth Narrowing





Optical Power Budget and Power Penalties

- Power budget : The minimum optical power available to overcome:
  - Attenuation + power penalties of the optical path between the transmitter and receiver
  - Calculated as the difference between the minimum transmitter launch power and the minimum receiver power.
- Channel insertion loss: the static loss of a link between a transmitter and receiver including the loss of the fiber, connectors, and splices.
- The power penalties of a link are not attributes of link attenuation (unless caused by a nonlinearity).
- Link power penalties include modal noise, relative intensity noise (RIN), intersymbol interference (ISI), mode partition noise, extinction ratio, and eye opening penalties including effects of fiber and amplifier nonlinearities.

Power Penalty

In general, we can asses the degradation of a transmission system due to the presence of certain impairments

Define the Power Penalty in the presence of impairments P_1', P_0', σ_1' and σ_0'

$$PP = -10\log\left(\frac{\dfrac{\Re(P_1' - P_0')}{\sigma_1' + \sigma_0'}}{\dfrac{\Re(P_1 - P_0)}{\sigma_1 + \sigma_0}}\right)$$

Power Penalties for other effects

- We consider in the next slides the power penalty for other effects, mostly related to the transmitter or receiver devices
  - Extinction ratio
  - Timing jitter
  - Laser intensity noise
- The power penalty is defined as the increase of optical power required to overcome a given effects with respect to an ideal systems

Extinction Ratio Power Penalty

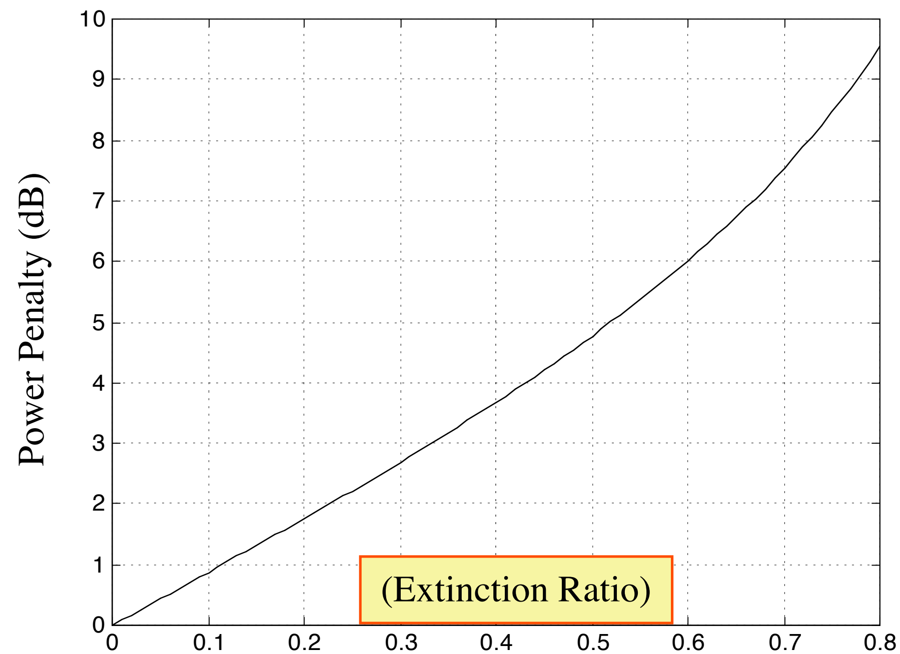
Transmitter Extinction Ratio†[1]

$$r_{ex} = \frac{P_0}{P_1}$$

$$P_0 = \frac{2\bar{P}}{r_{ex}+1}$$

$$P_1 = \frac{2r_{ex}\bar{P}}{r_{ex}+1}$$

$$PP_{ER} = -10\log\frac{r_{ex}-1}{r_{ex}+1}$$

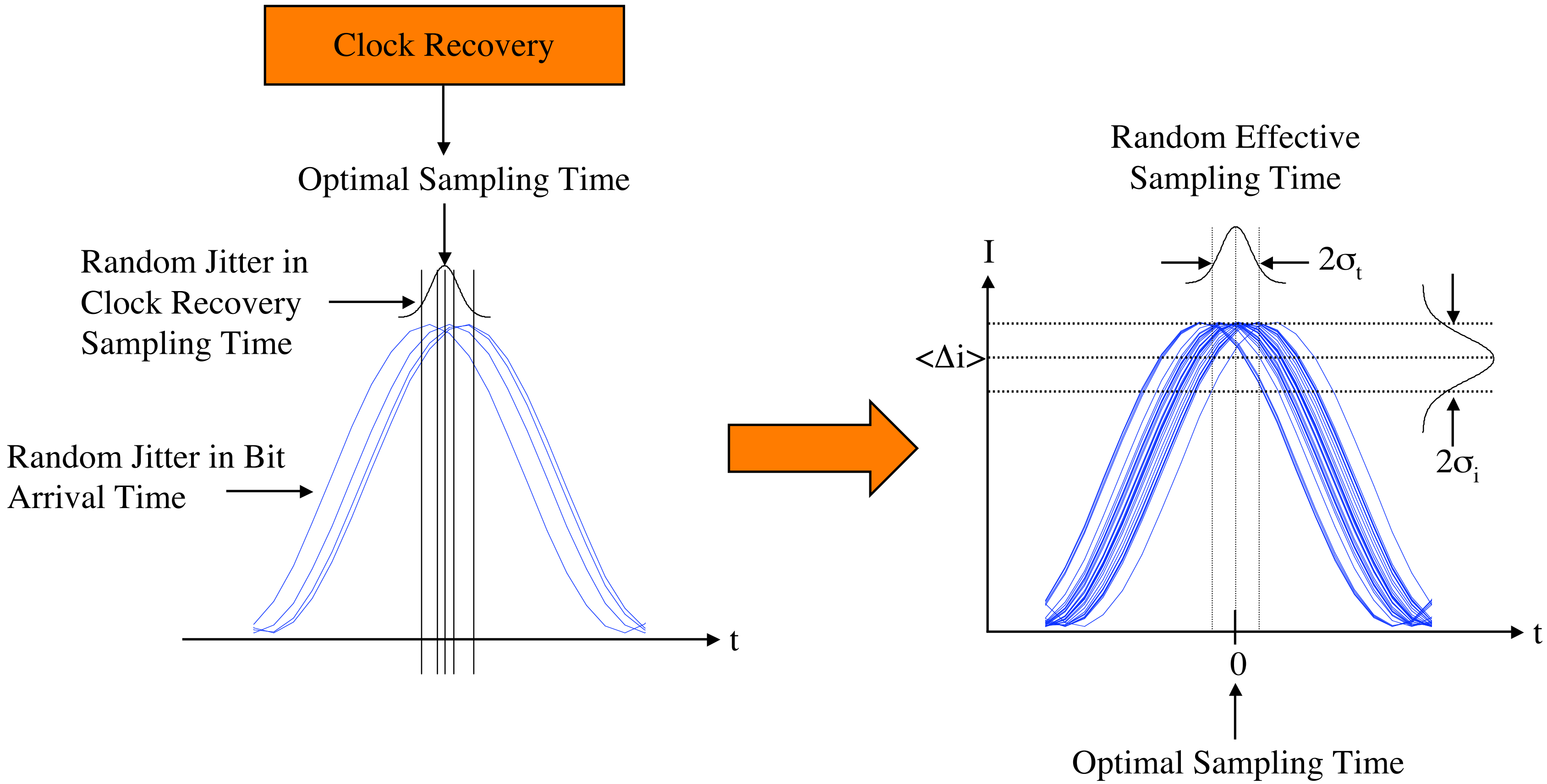


Note that in order to have negligible penalty, the extinction ratio should be not greater than 0.1, i.e, at least 10 dB
The typical value required in ITU standard is around 12 dB

† An alternate definition of extinction ratio is P_1/P_0 where $r_{ex} = \infty$ when $P_0 = 0$

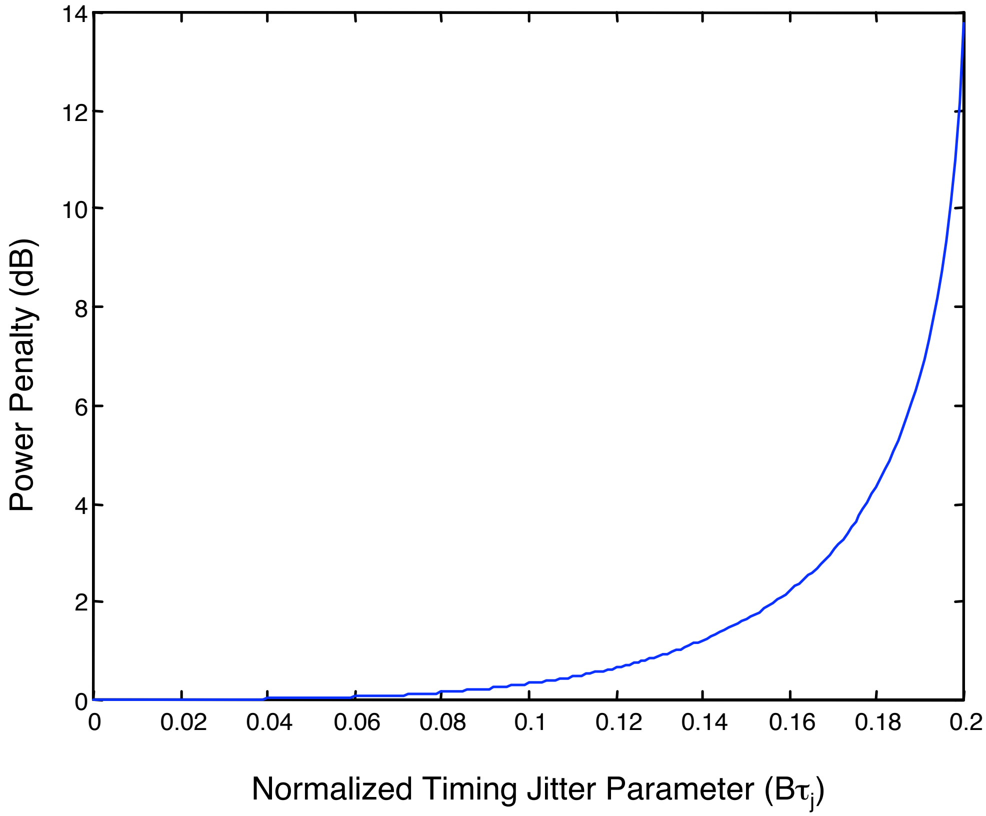
1 G. P. Agrawal, Fiber Optic Communications Systems, Wiley-Interscience

Timing Jitter



Timing Jitter Power Penalty

Assuming Gaussian timing jitter† $p(\Delta t) = \frac{1}{\tau_j \sqrt{2\pi}} \exp\left(-\frac{\Delta t^2}{2\tau_j^2}\right)$

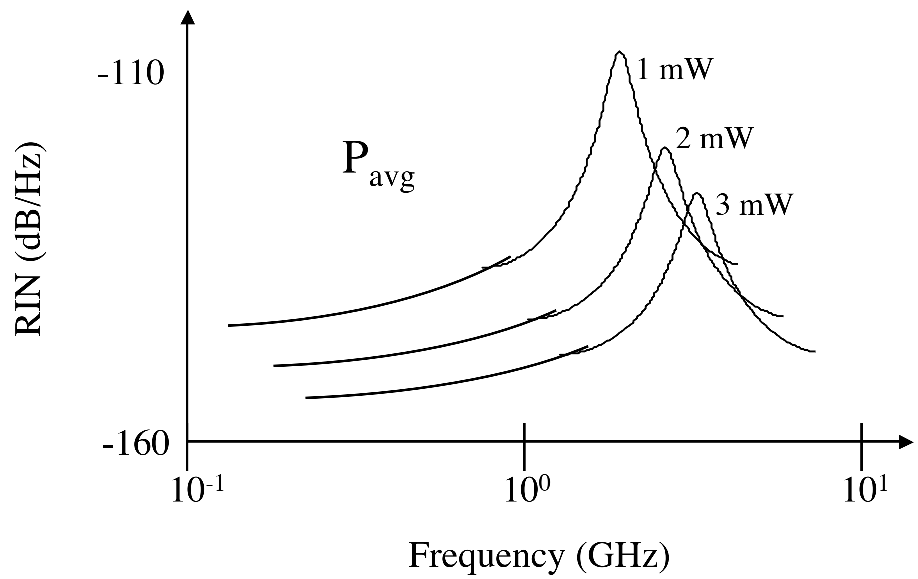


† G. P. Agrawal, Fiber Optic Communications Systems, Wiley-Interscience

Laser Intensity Noise

- Laser output exhibits random fluctuations in its output intensity, phase and frequency
  - This random behavior results in **Intensity Noise** and **Phase Noise**

Relative Intensity Noise (RIN) = P_{avg}/σ_p where σ_p is the noise variance



$$\sigma^2_{source} = \sigma^2_{RIN} + \sigma^2_{MPN}$$

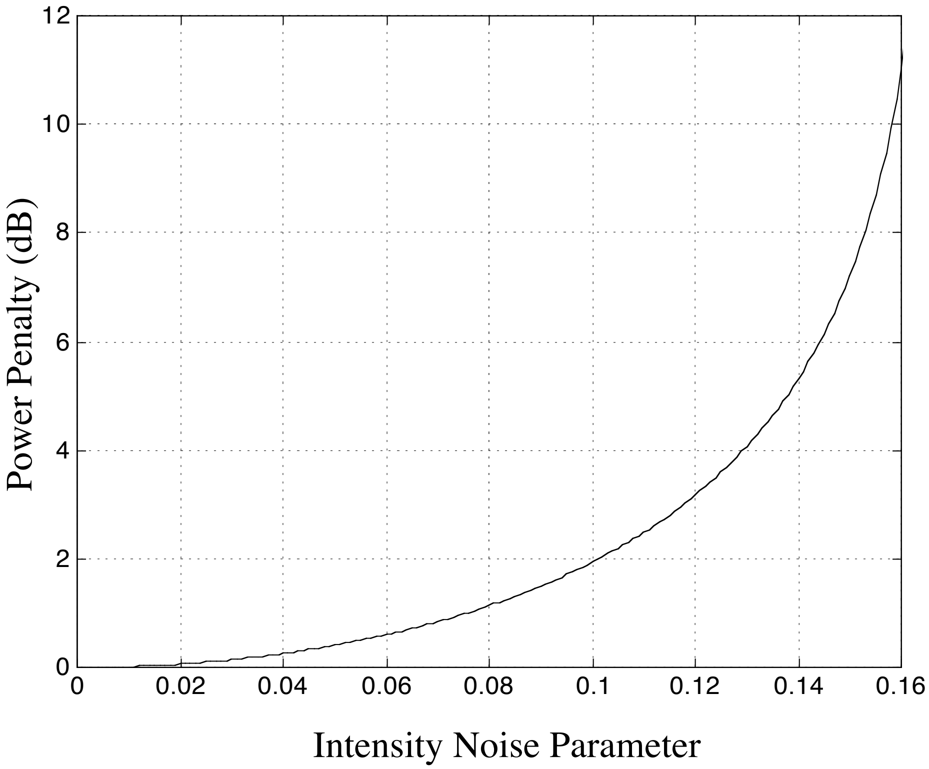
Intensity Noise Parameter Power Penalty

Intensity Noise Parameter

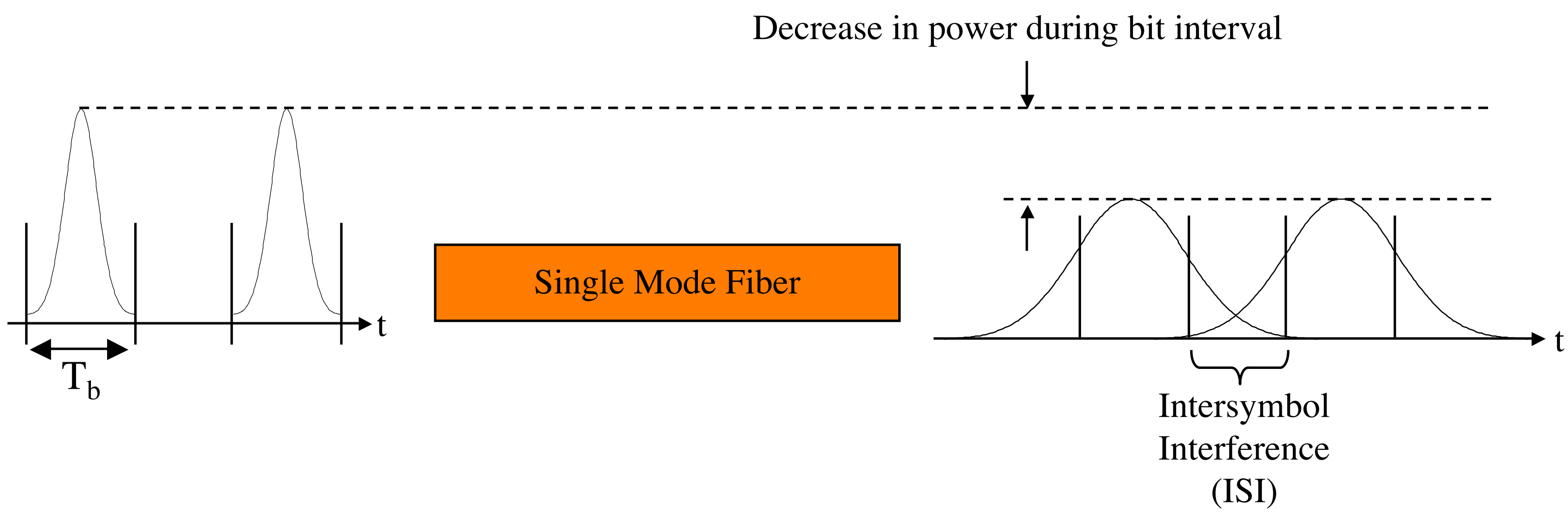
$$r_1^2 = \frac{1}{2\pi} \int_{-\infty}^{+\infty} RIN(\omega) d\omega$$

$$PP_{RIN} = -10 \log_{10}(1 - r_1^2 Q^2)$$

This power penalty is critical for analog systems and is typically not as critical for digital systems



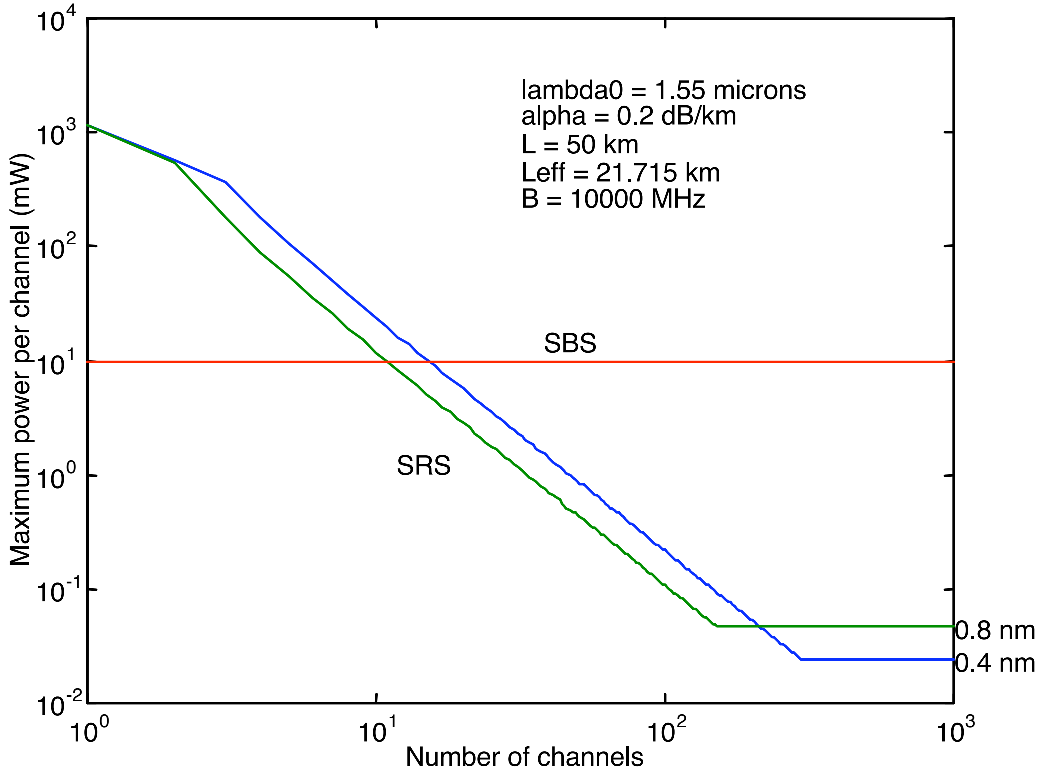
Dispersion Induced Power Penalty



Fiber Nonlinearities

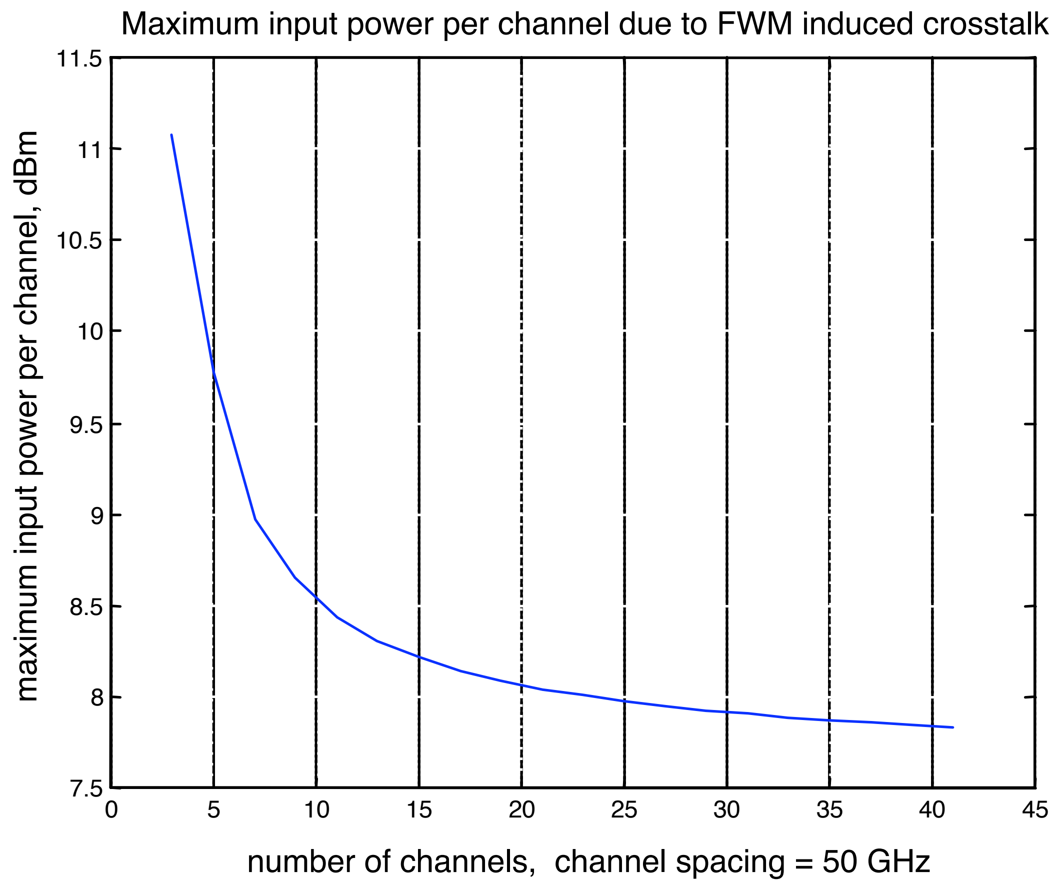
- In principle, we can continue to increase the optical power at the transmitter to overcome power penalties and limitations to SNR due to amplifier and receiver noise sources
  - But ! We if we try to increase the optical power per channel too much, the signal will start to degrade due to distortion and crosstalk caused by nonlinearities in the fiber and amplifiers
  - This means that the effective receiver sensitivity will be decreased or limited
  - We have to limit the input power injected into the fiber in order to avoid nonlinearities
  - The limits depend on the dominant nonlinear mechanism, the link and channel configurations and other link/network parameters

SRS and SBS



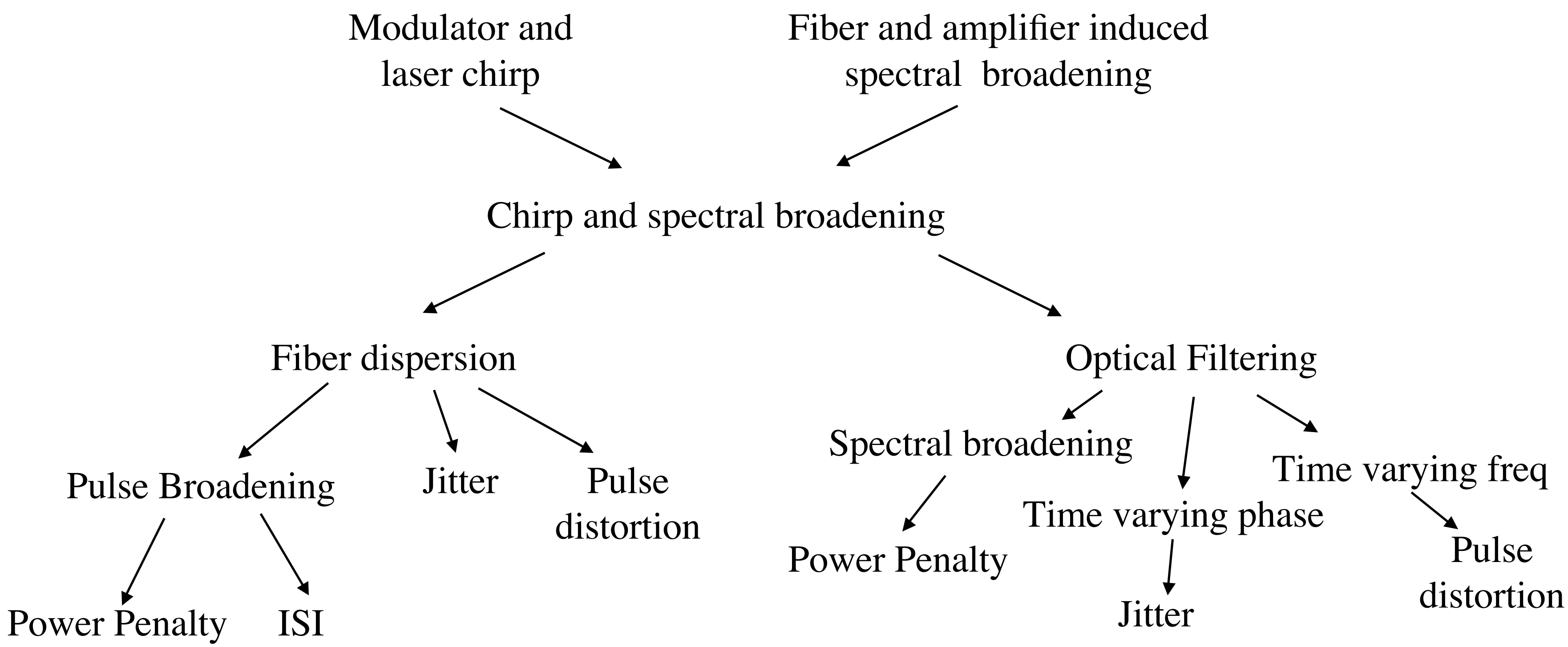
lambda0 = 1.55 microns
alpha = 0.2 dB/km
L = 50 km
Leff = 21.715 km
B = 10000 MHz
SBS
SRS
0.8 nm
0.4 nm
Maximum power per channel (mW)
Number of channels
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{0}
10^{1}
10^{2}
10^{3}

Fiber Four-Wave Mixing



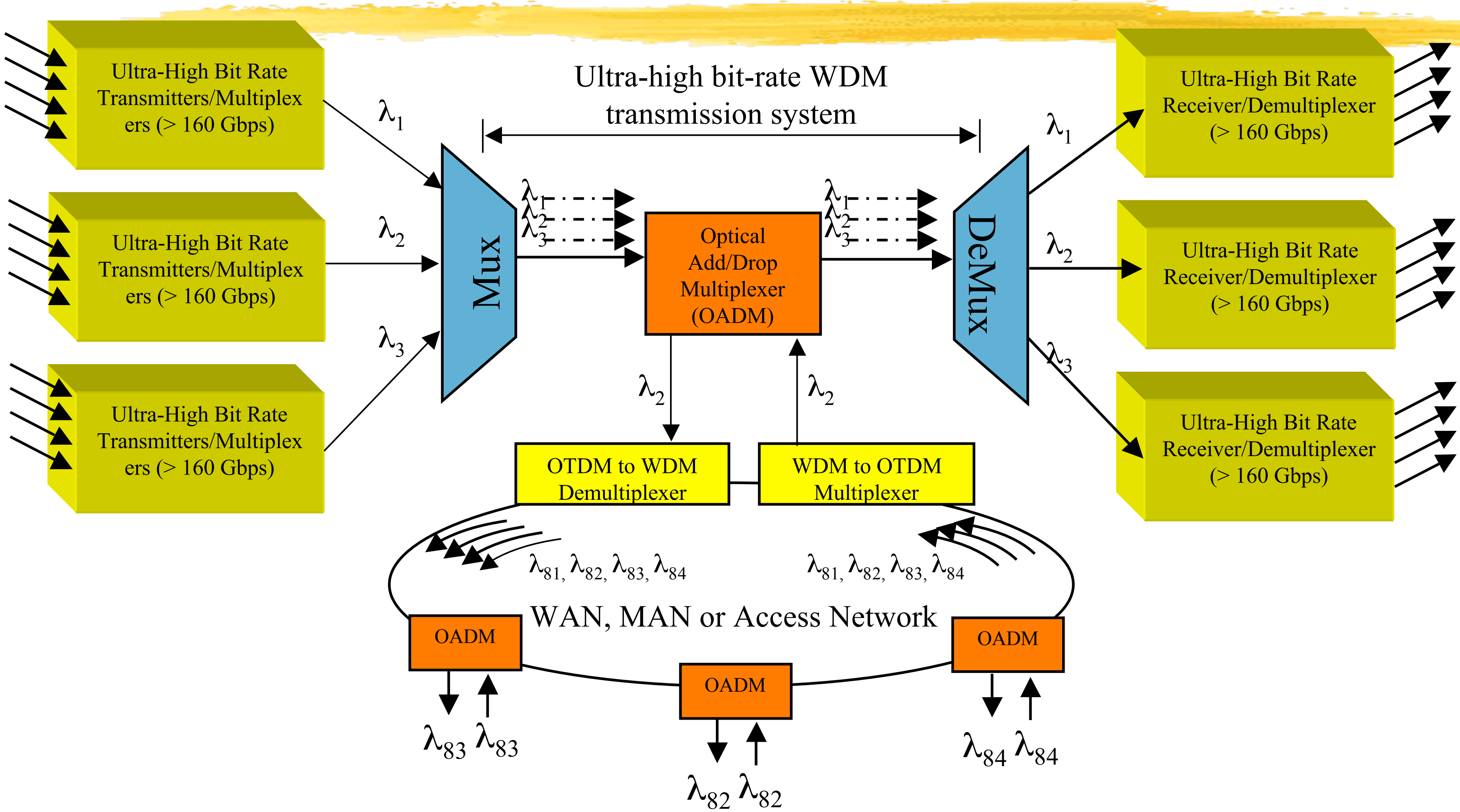
Spectral Power Penalty due to Modulation Chirp and Fiber and Amplifier Nonlinearities

We have already seen how modulation chirp can impart a time dependent frequency shift in the optical signal and produce spectral broadening. Later we will see how fiber and amplifier nonlinearities can produce this same effect.

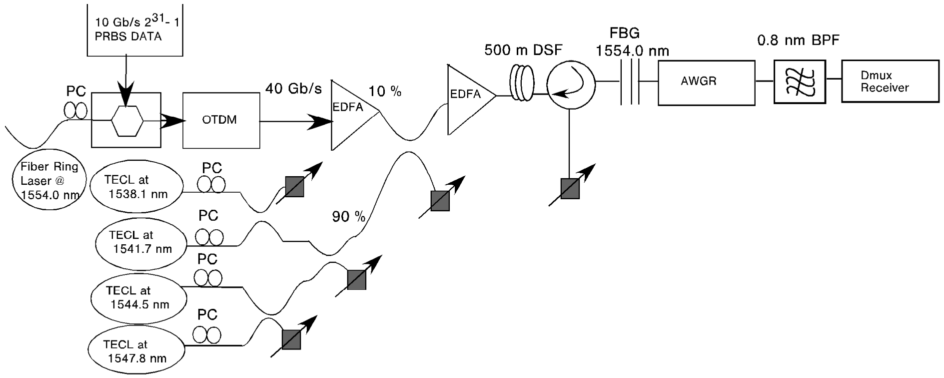


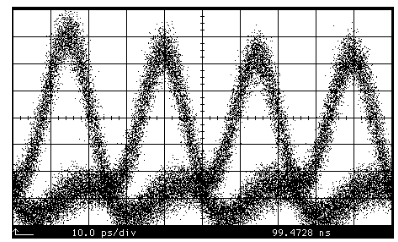
Optical Time Division Multiplexing (OTDM)

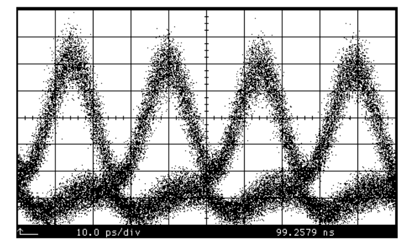
Agile-WDM/OTDM Network

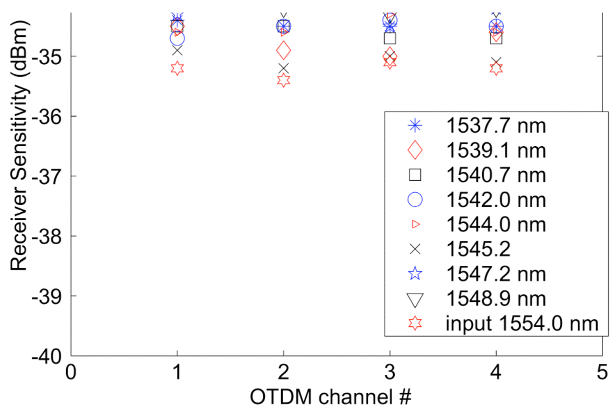


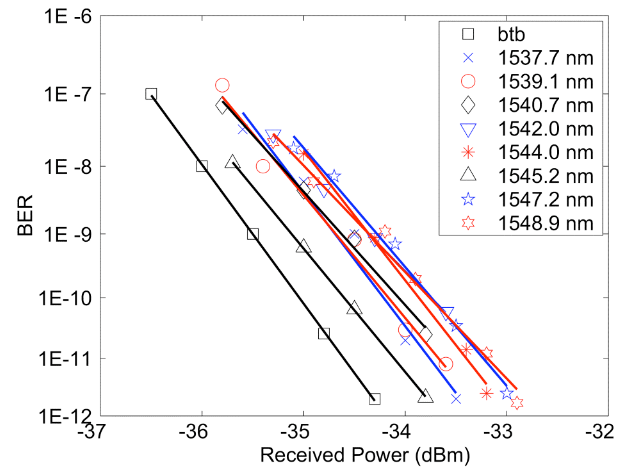
A Broadcast WDM-OTDM Technique based on 1 to 8 Multiple Wavelength Conversion with 2R Regeneration





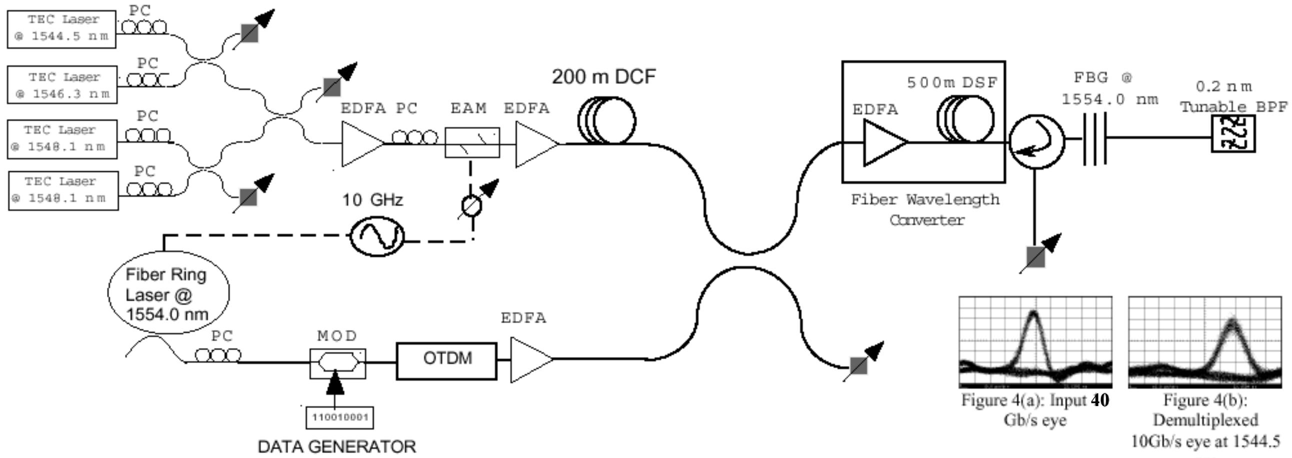






Lavanya Rau, Bengt-Erik Olsson and Daniel J. Blumenthal, OFC 2001.

OTDM to WDM Transmultiplexer



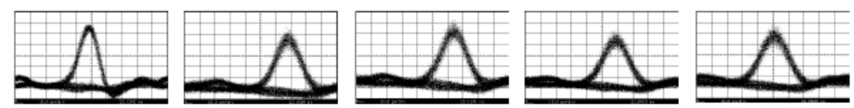
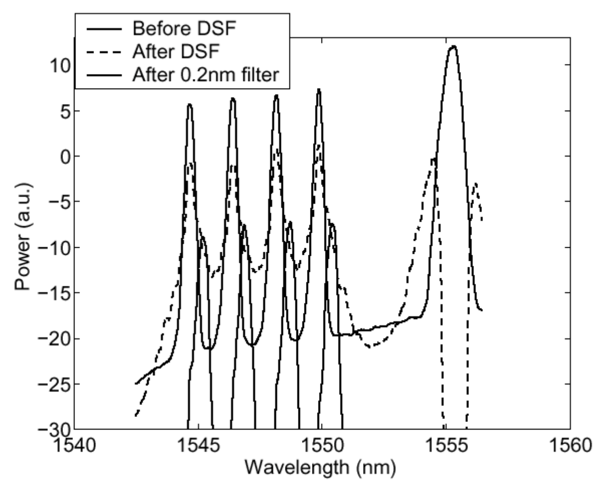
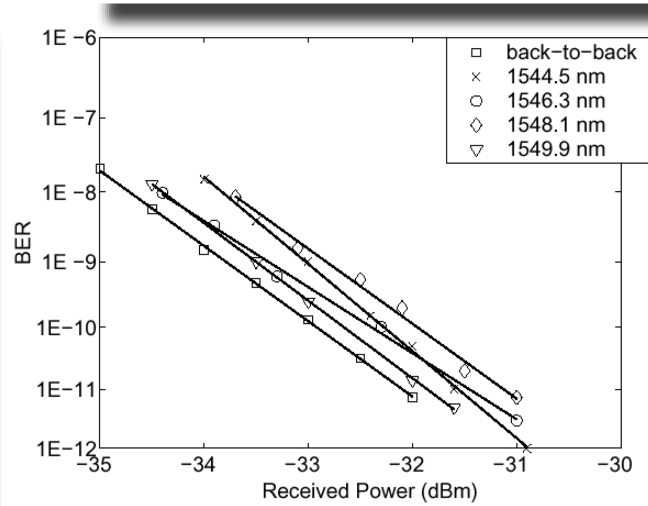


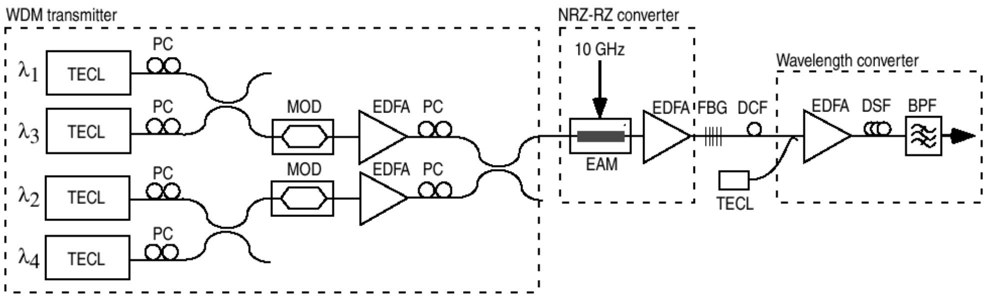
Figure 4(a): Input **40** Gb/s eye | Figure 4(b): Demultiplexed 10Gb/s eye at 1544.5 nm | Figure 4(c): Demultiplexed 10Gb/s eye at 1546.3 nm | Figure 4(d): Demultiplexed 10Gb/s eye at 1548.1 nm | Figure 4(e): Demultiplexed 10Gb/s eye at 1549.9 nm



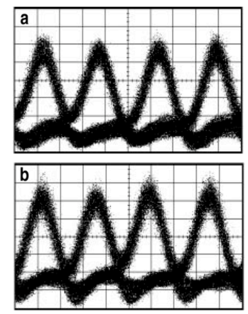


Lavanya Rau, Bengt-Erik Olsson and Daniel J. Blumenthal, Submitted to IEEE PTL, 2001

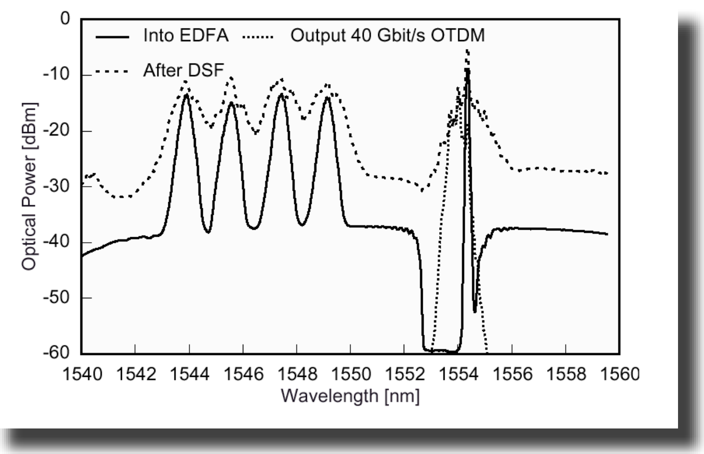
WDM to OTDM Transmultiplexer

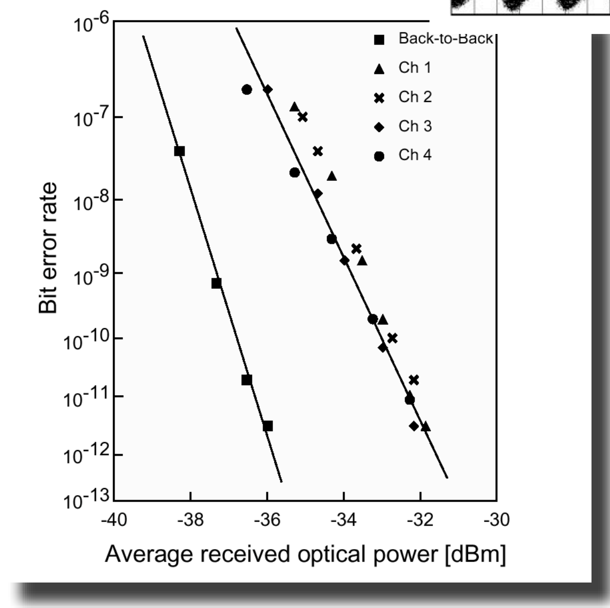


(4) 10 Gbps Channels



40 Gbps Channel





Bengt-Erik Olsson, Lavanya Rau and Daniel J. Blumenthal, IEEE PTL, September 2001