Optical Communication Systems (OPT428)

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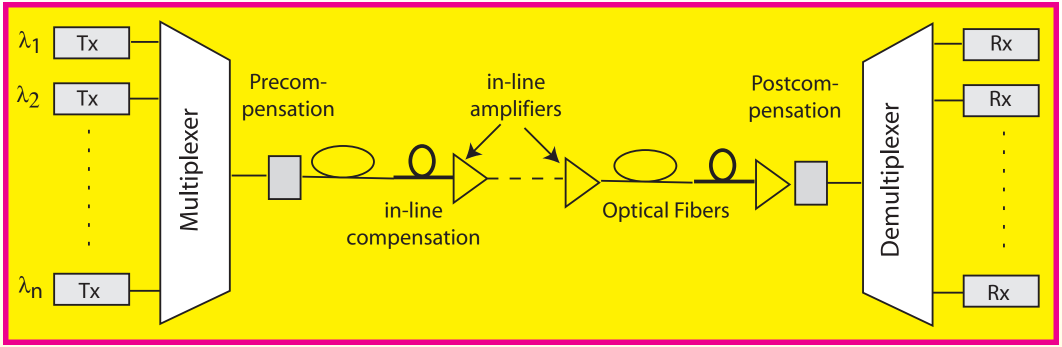
Chapter 9: WDM Systems

- Basic WDM Scheme
- Linear Degradation Mechanisms
- Nonlinear Crosstalk
- Cross-Phase Modulation
- Control of Nonlinear Effects
- Major Design Issues

Basic WDM Scheme



- Each channel operates at a distinct wavelength.
- Amplifiers used periodically for loss compensation.
- Pre-, post-, and in-line compensators used to manage dispersion of fiber link.
- Implementation of such a WDM scheme requires development of many new components such as multiplexers, demultiplexers, and optical filters.

Basic Concepts

- Relevant design parameters: N, B, and channel spacing $\Delta\nu_{\rm ch}$.
- NB = System capacity; $N\Delta\nu_{\rm ch}$ = Total signal bandwidth.
- WDM systems are classified as being coarse or dense depending on the value of $\Delta\nu_{\rm ch}$.
- Channel spacing >5 nm for coarse WDM but <1 nm for dense WDM systems.
- Spectral efficiency is defined as $\eta_s = B/\Delta\nu_{\rm ch}$.
- In practice, channel spacing $\Delta\nu_{\rm ch}$ exceeds B by a factor of 2 or more, resulting in $\eta_s < 0.5$ (b/s)/Hz.
- Considerable waste of fiber bandwidth in WDM systems.

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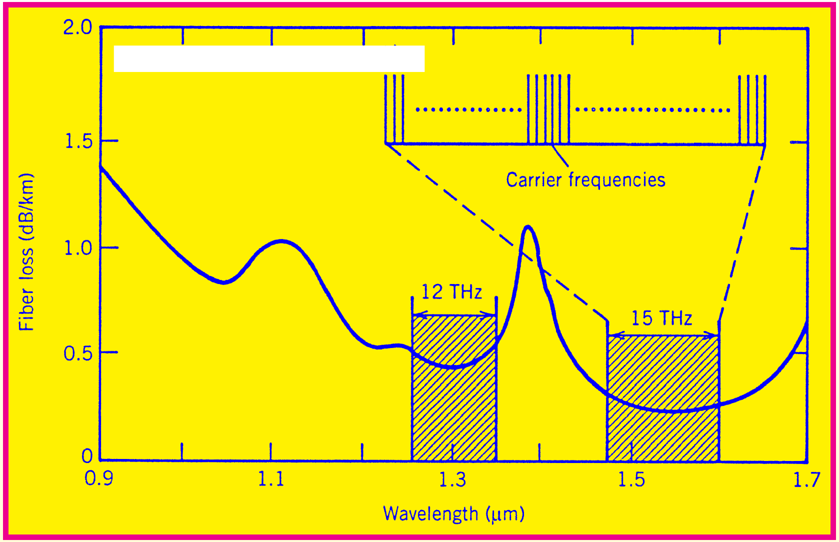
ITU Wavelength Grid

- Channel frequencies of WDM systems standardized by ITU.
- They lie on a 100-GHz ITU grid covering frequency range of 186 to 196 THz.
- This corresponds to a wavelength range 1530–1612 nm.
- C band covers 1530–1570 nm; L band covers 1570–1620 nm.
- Channel spacing for most commercial WDM systems is 100 GHz (0.8 nm at 1,552 nm).
- This value leads to only 10% spectral efficiency at 10 Gb/s.
- ITU has now specified channels with spacing of 25 and 50 GHz.
- 50-GHz channel spacing at 40 Gb/s yields 80% spectral efficiency.

Ultimate Capacity of WDM Systems



- Assume wavelength range from 1,300 to 1,600 nm is employed using dry fibers.
- Use channel spacing of 50 GHz (0.4 nm) for 40-Gb/s channels.
- 750 channels yield a system capacity of as 30 Tb/s.

Ultimate Capacity of WDM Systems

- Many factors limit the use of the entire low-loss window.
- Number of channels is often limited by the bandwidth over which amplifiers can provide uniform gain.
- EDFA bandwidth is limited to around 40 nm.
- Raman amplification can solve the bandwidth problem to some extent.
- Other factors include: wavelength stability of DFB lasers, signal degradation from nonlinear effects, and interchannel crosstalk.
- High-capacity WDM links need components such as channel demultiplexers, optical filters, add-drop multiplexers, etc.

Experimental Results

- In a 1985 experiment, ten 2-Gb/s channels were transmitted over 68 km.
- A capacity of 340 Gb/s was demonstrated in 1995 by transmitting 17 channels, each operating at 20 Gb/s, over 150 km.
- This was followed within a year by several experiments that realized a capacity of 1 Tb/s.
- By 2001, the capacity of WDM systems exceeded 10 Tb/s in laboratory experiments.
- In one experiment, 273 channels, spaced 0.4 nm apart at 40 Gb/s, were transmitted over 117 km, resulting in a capacity of 11 Tb/s and a NBL product of 1.28 (Pb/s)-km.

Record-Setting WDM Experiments

High-capacity WDM transmission experiments

Channels N	Capacity NB (Tb/s)	Distance L (km)	NBL Product [(Pb/s)-km]	Conference and Year
256	10.24	100	1.02	OFC 2001
273	10.92	117	1.28	OFC 2001
128	5.12	1,280	6.66	ECOC 2002
40	1.6	5,200	8.32	ECOC 2002
159	6.4	2,100	14.44	ECOC 2002
80	3.2	5,200	16.64	ECOC 2002
160	6.4	3,200	20.48	OFC 2003
373	3.73	11,000	41.03	OFC 2003

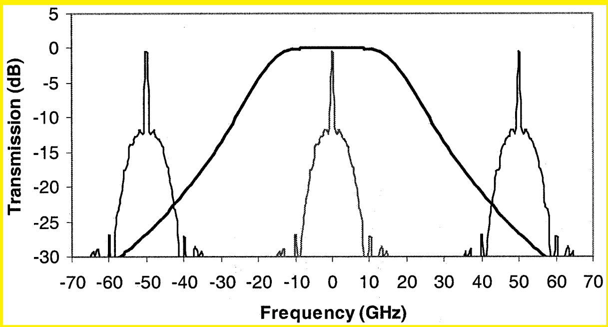
Long-Haul WDM Experiments

- In a 1996 experiment, 20 channels at 5 Gb/s were sent over 9100 km using forward-error-correction.
- In a 2003 experiment, a 3.73-Tb/s WDM signal (373 channels at 10 Gb/s) was transmitted over 11,000 km.
- This should be compared with the first fiber-optic cable laid across the Atlantic Ocean (TAT-8); it operated at 0.27 Gb/s with $NBL \approx 1.5$ (Tb/s)-km.
- On the commercial side, WDM links operating at 160 Gb/s (16 channels at 10 Gb/s) appeared in 1998.
- By 2001, WDM systems with a capacity of 1.6 Tb/s (160 channels at 10 Gb/s) were available.

Crosstalk in WDM Systems

- System performance degrades whenever power from one channel leaks into another.
- Such a power transfer can occur because of the nonlinear effects in optical fibers (nonlinear crosstalk).
- Crosstalk occurs even in a perfectly linear channel because of imperfections in WDM components.
- Linear crosstalk can be classified into two categories.
- Heterowavelength or Out-of-band crosstalk: Leaked power is at a different wavelength from the channel wavelength.
- Homowavelength or In-band crosstalk: Leaked power is at the same wavelength as the channel wavelength.

Out-of-Band Linear Crosstalk



- Introduced by an optical filter if its passband leaks other channels.
- A small amount of power from neighboring channels can leak when channels are not spaced far apart.
- A filter with 40-GHz (FWHM) is used for 10-Gb/s channels, spaced 50 GHz apart.
- In spite of relatively sharp spectral edges, transmissivity is -26 dB for neighboring channels.

Crosstalk Power Penalty

- Power leaked acts as noise and is a source of linear crosstalk.
- Power after filter: $P = P_m + \sum_{n \neq m}^{N} T_{mn} P_n$.
- Photocurrent at receiver: $I = R_m P_m + \sum_{n \neq m}^{N} R_n T_{mn} P_n \equiv I_{\mathrm{ch}} + I_X$.
- Crosstalk penalty: $\delta_X = 10 \log_{10}\left(1 + \frac{\sum_{n \neq m}^{N} R_n T_{mn} P_n}{R_m P_m}\right)$.
- Assuming equal powers and same responsivities,

$$\delta_X \approx 10 \log_{10}(1 + X).$$

- $X = \sum_{n \neq m}^{N} T_{mn}$ represents the fraction of total power leaked into a specific channel from all other channels.

Filter-Induced Crosstalk

- Numerical value of X depends on filter's passband.
- X can be as large as 0.1 to produce $<$0.5-dB penalty.
- Out-of-band crosstalk becomes of concern only when channels are so closely spaced that their spectra begin to overlap.
- Power penalty has been calculated for Fabry–Perot filters.
- In general, power penalty depends on the finesse of the filter.
- Spectral efficiency can approach 50% without much penalty when Fabry–Perot filters are employed.

In-band Linear Crosstalk

- Occurs for WDM components used for routing and switching.
- Its origin can be understood by focusing on a router.
- A router with $N+1$ input and outport ports has $(N+1)^2$ combinations for splitting $N+1$ wavelengths.
- Consider output at one wavelength, say λ_0.
- Among the $N(N+2)$ interfering components that accompany desired signal, N have the same wavelength.
- Total electrical field at the receiver can be written as

$$E_r(t) = \left[A_0(t) + \sum_{n=1}^{N} A_n(t)\right] \exp(-i\omega_0 t).$$

- Coherent nature of in-band crosstalk is evident from this equation.

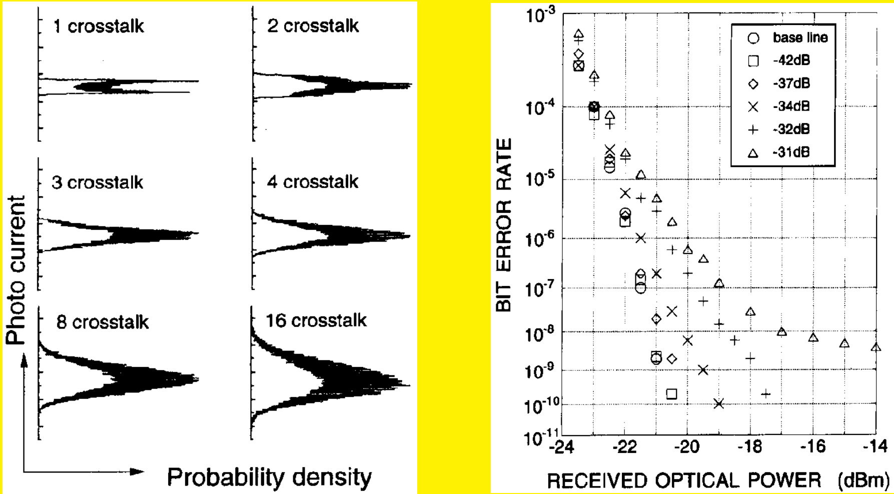
In-band Linear Crosstalk

- Receiver current $I(t) = R_d|E_r(t)|^2$ contains interference or beat terms, in addition to the desired signal.
- Signal–crosstalk beating results in terms like $A_0^* A_n$.
- Crosstalk–crosstalk beating results in terms like $A_k^* A_n$; these are relatively small and one can ignore them.

$$I(t) \approx R_d P_0(t) + 2R_d \sum_{n=1}^{N} \sqrt{P_0(t)P_n(t)} \cos[\phi_0(t) - \phi_n(t)].$$

- Each term acts as an independent random variable.
- Use $I(t) = R_d(P_0 + \Delta P)$ and treat crosstalk as intensity noise.
- Even though each term in ΔP is not Gaussian, their sum becomes Gaussian for large N (central limit theorem).

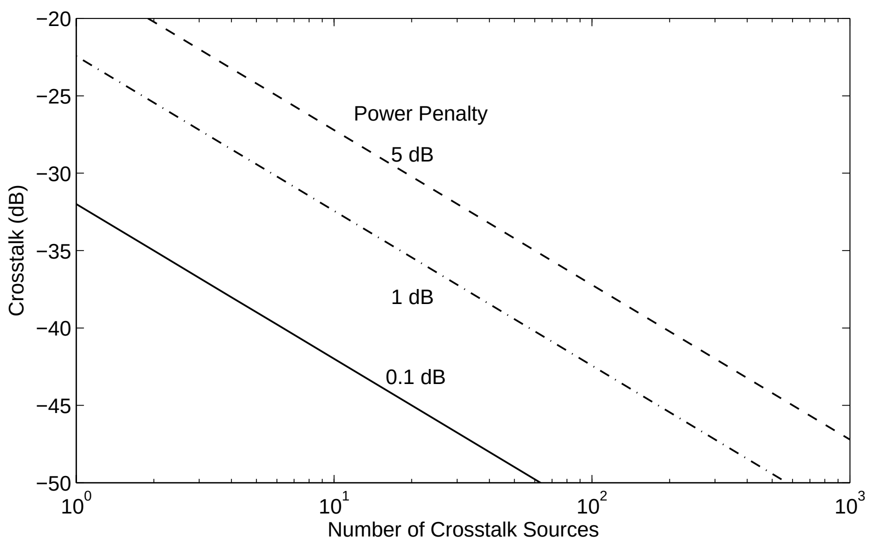
In-band Linear Crosstalk



(a) (b)

- Experimentally measured probability distributions.
- BER curves were measured for $N = 16$ for $X = P_n/P_0$.
- Considerable power penalty occurs for $X > -35$ dB.

In-band Linear Crosstalk

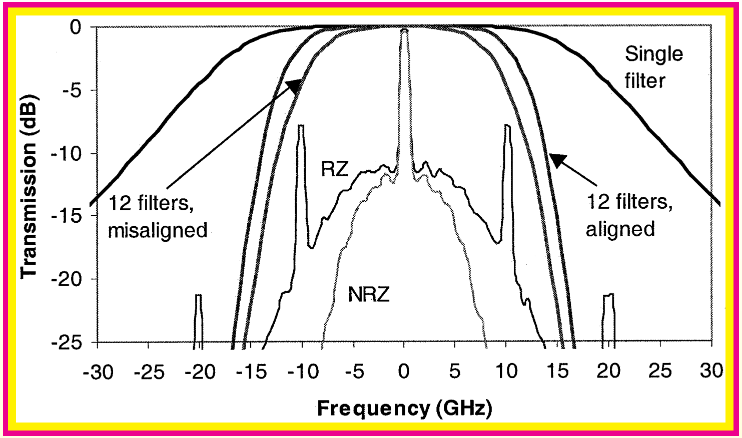


- Power penalty $\delta_X = -10\log_{10}(1 - r_X^2 Q^2)$ with $r_X^2 = NX$.
- Penalty <1 dB if $r_X < 0.1$ or $XN < -20$ dB.
- X must be below −40 dB for $N = 100$, a relatively stringent requirement.

Filter-Induced Signal Distortion

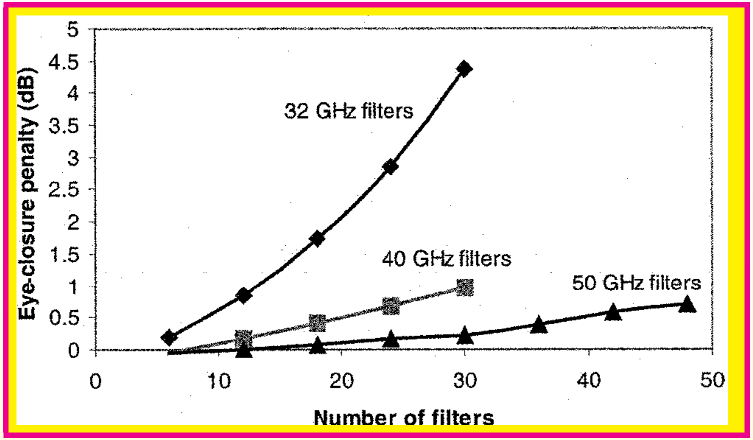
- Filters are designed to be wide enough to pass the signal without any distortion.
- If signal passes through a large number of optical filters, one must consider the effects of filter concatenation.
- Even when a signal passes through the same filter twice, effective filter bandwidth becomes narrower because $H^2(\omega)$ is a sharper function of frequency than $H(\omega)$.
- Cascading of many filters may narrow bandwidth enough to produce clipping of the signal spectrum.
- Figure 9.6 shows transmission after 12 third-order Butterworth filters of 36-GHz bandwidth.

Filter-Induced Signal Distortion



- It is difficult to align filters precisely.
- Effective bandwidth is reduced further if filters are misaligned within ± 5 GHz.
- Spectrum of a 10-Gb/s signal is clipped for RZ format even when filter bandwidth is 36 GHz.

Filter-Induced Signal Distortion

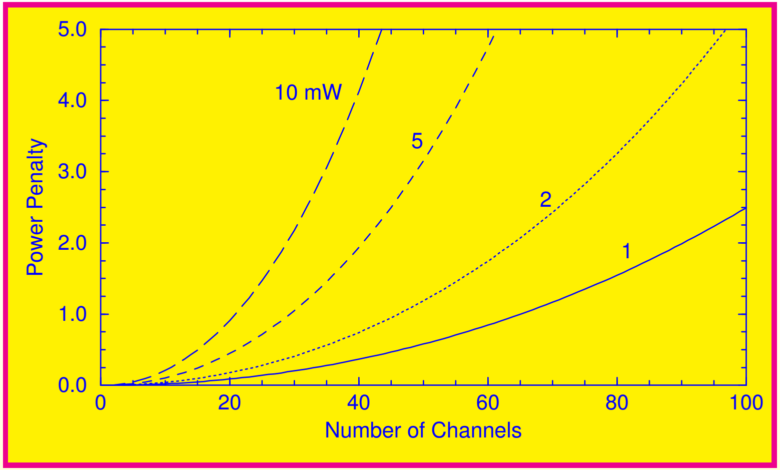


- Eye-closure penalty as a function of the number of filters for a 10-Gb/s RZ signal with 50% duty cycle.
- A negligible penalty occurs when filter bandwidth is 50 GHz.
- It increases rapidly as the bandwidth is reduced below 40 GHz.
- If filter bandwidth is increased, spectral efficiency is reduced.

Nonlinear Raman Crosstalk

- SRS not of concern for single-channel systems because of its high threshold (about 500 mW).
- In the case of WDM systems, fiber acts as a Raman amplifier.
- Long-wavelength channels are amplified by short-wavelength channels.
- Power transfer depends on the bit pattern: amplification occurs only when 1 bits are present in both channels simultaneously.
- SRS induces power fluctuations (noise) in all channels.
- Shortest-wavelength channel is most depleted.
- One can estimate Raman crosstalk from noise level of this channel.

Raman-Induced Power Penalty



- Power penalty $\delta_R = -10\log(1 - D_R)$, where

$$D_R = \sum_{m=2}^{M} g_R(\Omega_m) P_{\text{ch}} L_{\text{eff}}/A_{\text{eff}}.$$

- P_{ch} should be below 1 mW when $M > 70$.

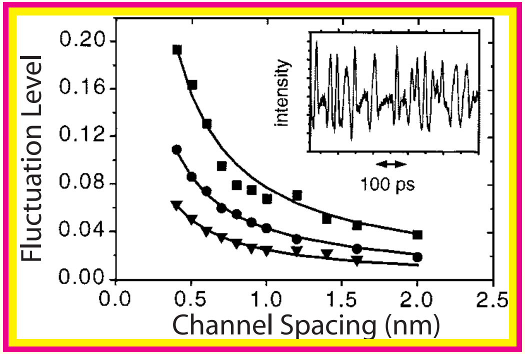
Four-Wave Mixing

- FWM generates new waves at frequencies $\omega_{ijk} = \omega_i + \omega_j - \omega_k$.
- In the case of equally spaced channels, new frequencies coincide with the existing frequencies and produce in-band crosstalk.
- In the case of nonuniform channel spacing, most FWM components fall in between the channels and produce out-of-band crosstalk.
- Nonuniform channel spacing not practical because many WDM components require equal channel spacings.
- A practical solution offered by the periodic dispersion management technique.
- Dispersion of all fibers is high locally but its average value is made relatively low.

Cross-Phase Modulation

- XPM coupling among WDM channels leads to both amplitude fluctuations and timing jitter.
- XPM-induced phase shift would not affect system performance if dispersive effects were negligible.
- Any dispersion in fiber converts pattern-dependent phase shifts to power fluctuations, reducing the SNR at the receiver.
- Such XPM-induced power fluctuations become quite large for fibers with large dispersion.
- In a dispersion-managed system, they also depend on the dispersion map employed.

XPM-Induced Power Fluctuations

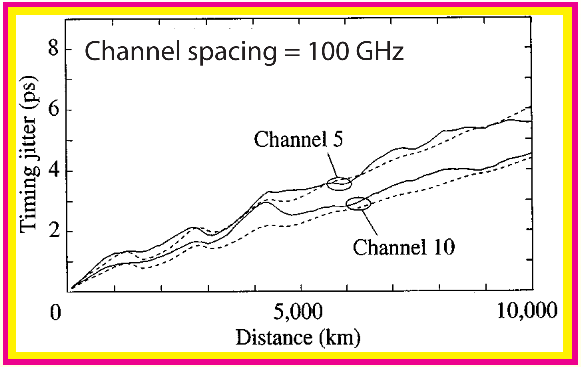


- XPM-induced power fluctuations depend considerably on channel spacing and become less pronounced as it increases.
- Measured standard deviation of probe fluctuations as a function of channel spacing with (circles) and without (squares) dispersion compensation.
- Triangles represent the data obtained under field conditions.
- Inset shows probe fluctuations for $\Delta\lambda = 0.4$ nm.

XPM-Induced Timing Jitter

- XPM interaction among channels can induce considerable timing jitter.
- Pulses belonging to different channels travel at different speeds because of group-velocity mismatch.
- They collide with each other at a rate that depends on channel spacing.
- Since XPM can occur only when pulses overlap in time domain, walk-off effects play an important role.
- Timing jitter results frequency shifts experienced by pulses.
- This jitter is a major source of degradation for all WDM systems.

XPM-Induced Timing Jitter

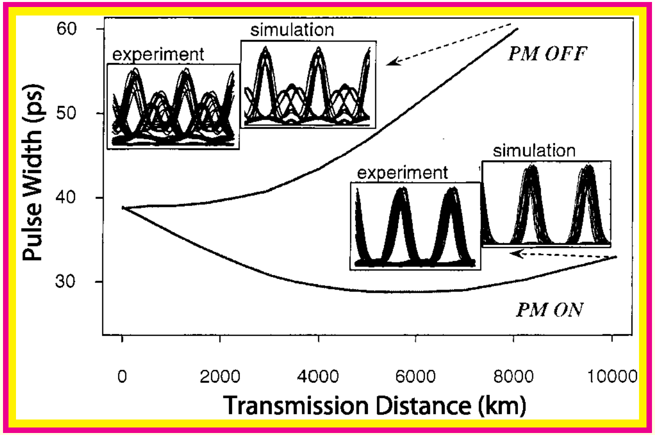


- Growth of timing jitter as a function of distance for a 10-channel WDM system designed with a 100-km periodic dispersion map.
- Numerical (solid curves) and semi-analytic (dashed curves) results are compared for 10-Gb/s channels spaced apart by 100 GHz.
- Timing jitter is larger for the central channel.
- This is understood by noting that pulses in central channel collide with pulses in channels located on both sides.

Control of Nonlinear Effects

- Many techniques can reduce the impact of nonlinear effects.
- Optimization of dispersion maps can help.
- Experiments show that the use of precompensation helps to improve performance of long-haul systems.
- Such a scheme is known as the CRZ format because precompensation is equivalent to chirping optical pulses.
- A phase modulator can also be used to prechirp optical pulses.
- The reason behind improved system performance with prechirping is partly related to the fact that a chirped pulse undergoes compression initially when $\beta_2 C < 0$.

Phase modulation of Bit Sream

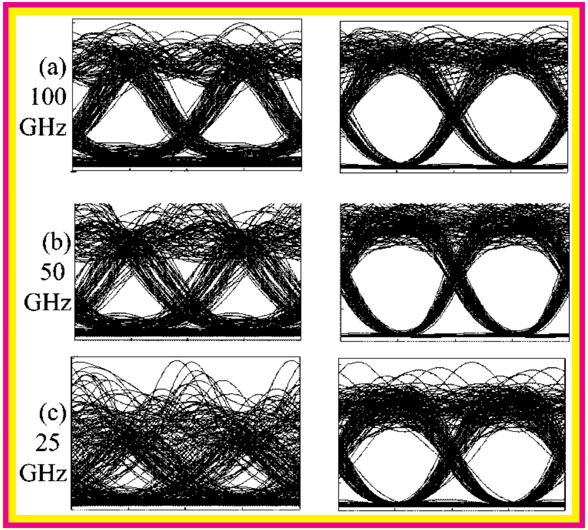


- Evolution of pulse width along the link length in one channel of a 16-channel WDM system.
- Channels operated at 10 Gb/s with a channel spacing of 100 GHz.
- A periodic dispersion map employed with a small amount of residual anomalous dispersion per map period.

Phase Conjugation of Bit Stream

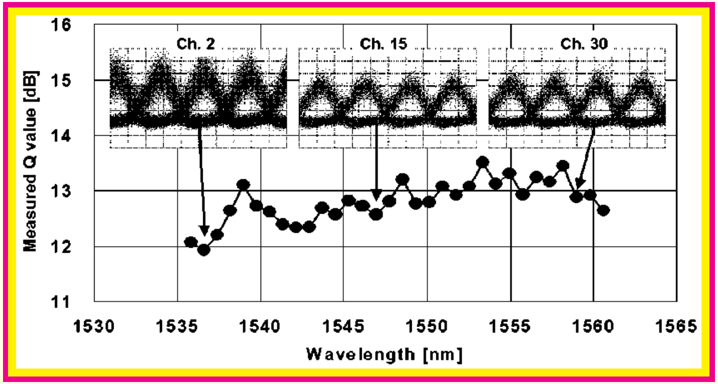
- XPM-induced distortion can be removed through mid-span phase conjugation.
- Reason: Dispersion changes sign, and XPM effects nearly vanish.
- XPM-induced frequency shifts introduced in the first half of fiber link change sign and are cancelled in the second half.
- Figure 9.18 simulates numerically a 5-channel WDM system at 10 Gb/s.
- Each NRZ-format channel launched with 1 mW of power.
- Amplifiers are spaced 80 km apart. Dispersion of standard fibers in each section is fully compensated using DCFs.

Phase Conjugation of Bit Stream



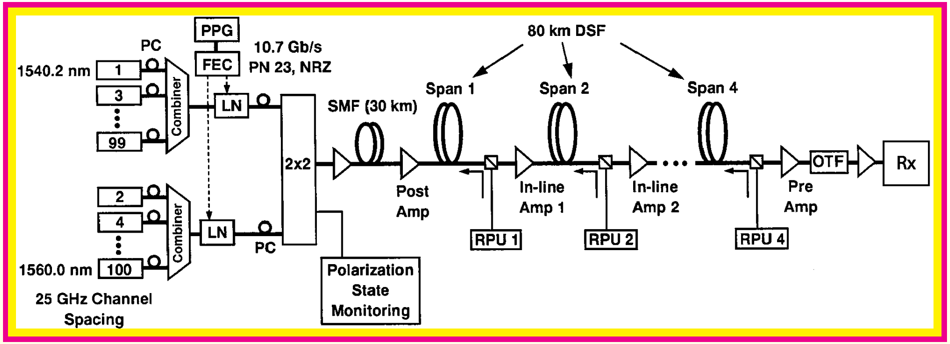
- Numerically simulated eye patterns at a distance of 2560 km for a channel spacing of (a) 100, (b) 50, and (c) 25 GHz.
- Right column shows the improvement realized with phase conjugator placed at a distance of 1280 km.

Use of a Dense Dispersion Map



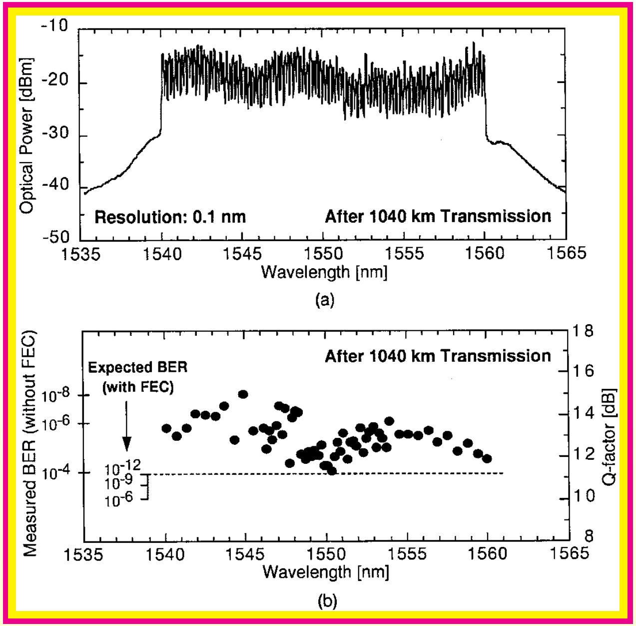
- In a dense dispersion map amplifier spacing $L_A = mL_{\text{map}}$.
- 32 channels at 40 Gb/s could be transmitted over 3000 km when $m = 2$ and $L_A = 50$ km.
- Measured Q factors were large enough that this system can operate with a BER below 10^{-9} after forward error correction.

Use of Raman Amplification



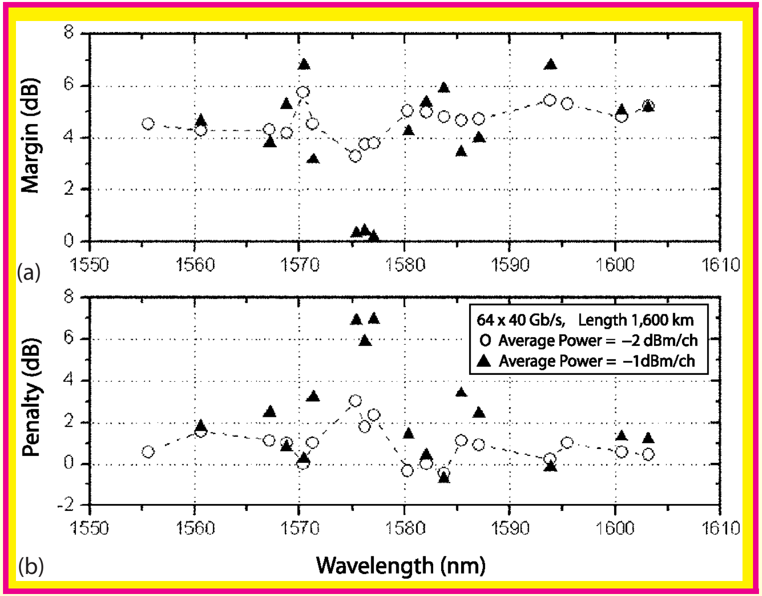
- Nonlinear effects can be controlled through Raman amplification.
- Its use allows one to obtain the same value of the Q factor at much lower launch powers because of reduced noise.
- Lower launch power also helps in reducing the XPM effects in WDM systems.
- 100 channels with 25-GHz channel spacing could be transmitted.

Use of Raman Amplification



- (a) Optical spectrum and (b) measured Q factors after 320 km for the 100-channel WDM system.
- Dotted line shows the Q for a BER below 10^{-12} with FEC.

Use of Raman Amplification

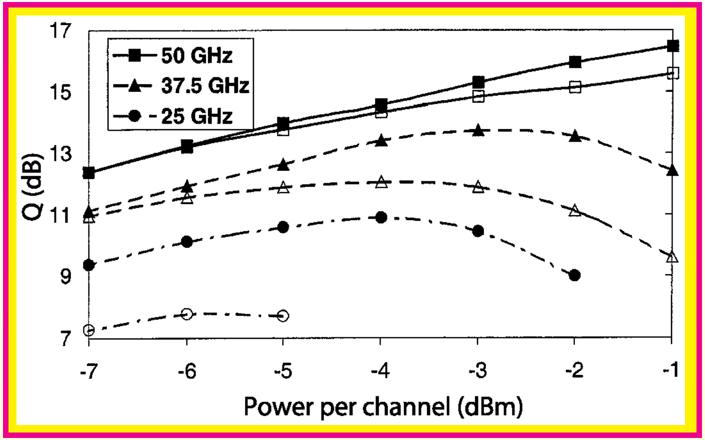


- In 2004, 64 channels at 40 Gb/s were transmitted over 1600 km.
- System margin is defined as the difference between the received and required optical SNR.

Polarization Interleaving of Channels

- Bit streams in neighboring channels are made orthogonally polarized.
- Such a scheme is relatively easy to implement in practice.
- Polarization interleaving helps because XPM coupling depend on the SOPs of the interacting channels.
- Factor of 2 appearing in the XPM-induced phase shift is replaced with 2/3 for orthogonally polarized channels.
- As a result, interchannel collisions produce smaller phase shifts and lead to much less amplitude and timing jitters.
- This technique is used in most WDM systems.

Polarization Interleaving of Channels

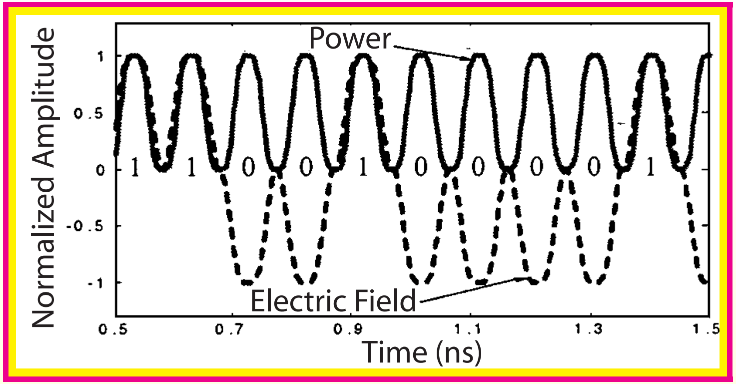


- Q factors after 9,000 km for three channel spacings.
- Neighboring channels are copolarized (empty symbols) or orthogonally polarized (filled symbols).
- Polarization interleaving helps for 25-GHz channel spacing but its advantage disappears for 50-GHz channels because of PMD.

Use of DPSK Format

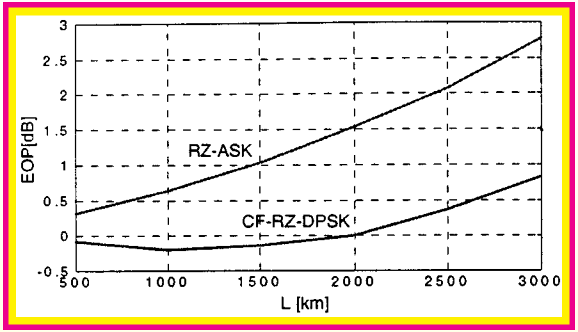
- XPM penalties are reduced for the RZ-DPSK format.
- XPM would be harmless if channel powers were constant in time because all XPM-induced phase shifts become time-independent, producing no frequency and temporal shifts.
- In RZ-DPSK systems, even though information is coded through phase shifts, an optical pulse is present in all bit slots.
- As a result, XPM effects cannot be eliminated.
- Channel powers vary in a periodic fashion under such conditions.
- XPM effects are reduced because all bits experience the same bit patterns in neighboring channels.

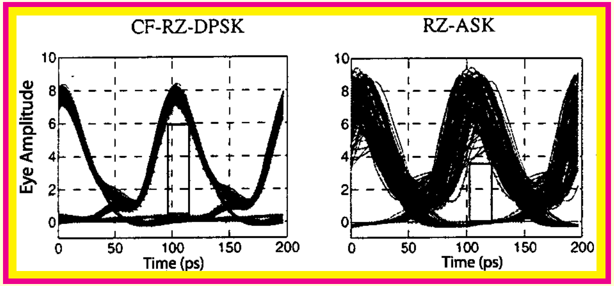
DPSK Format



- Temporal variations of the electric field and optical power for a 10-Gb/s channel coded using the RZ-DPSK format.
- Optical power varies in a periodic fashion.
- This periodicity helps to reduce the impact of XPM.

Advantage of DPSK Format





- Eye-opening penalty for RZ-ASK and RZ-DPSK formats.
- Eye diagrams at a distance of 3,000 km for the two formats.

Major Design Issues

- Design of modern high-capacity WDM systems with a large number of channels is not a simple task.
- Major design issues include
  - ⋆ Spectral Efficiency
  - ⋆ Dispersion Fluctuations
  - ⋆ PMD and Polarization-Dependent Losses
  - ⋆ Wavelength Stability

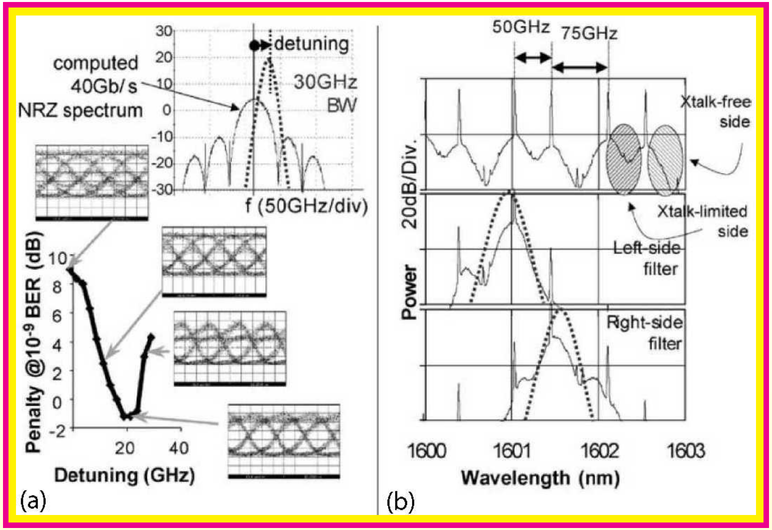
Spectral Efficiency

- Spectral efficiency is defined as $\eta_s = B/\Delta\nu_{\mathrm{ch}}$.
- Most WDM systems have $\eta_s \le 0.2$ (b/s)/Hz.
- Several experiments transmitted 40-Gb/s channels with 50 GHz spacing, resulting of $\eta_s = 0.8$ (b/s)/Hz.
- Such WDM systems employ modulation formats that are different than the standard RZ and NRZ formats.
- Prefiltering of signal at the transmitter end can also help.
- In vestigial sideband (VSB) transmission, one sideband of the signal is filtered optically.

Optical Filtering at Receiver End

- Suppressed sideband is reconstructed partially during transmission by the nonlinear effects occurring within the fiber.
- An alternative scheme transmits the whole spectrum but employs an optical filter at the receiver end to select only one sideband.
- Spectral efficiency is enhanced by using a nonuniform channel allocation pattern.
- Channel spacing alternates between 50 and 75 GHz for 40-Gb/s channels, resulting in a spectral efficiency of 0.64 (b/s)/Hz.
- At the receiver end, channels are selected with a 30-GHz filter that is detuned by 20 GHz or so toward the 75 GHz-spaced channel.
- With this arrangement, one always selects the sideband experiencing the smallest overlap with adjacent channels.

Experimental Results

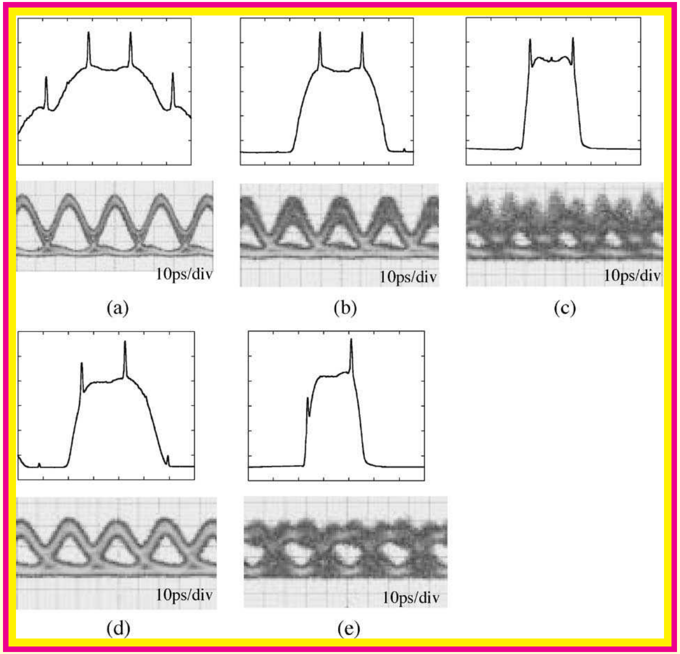


- (a) Measured power penalty and (b) spectra of filtered channels at the receiver for channels alternatively spaced by 50 and 75 GHz.
- This scheme was used in 2000 to realize a record capacity of 10.2 Tb/s (256 channels at 40 Gb/s) over 100 km.

Asymmetric Filtering at Transmitter

- Channel bandwidth can be reduced with the CSRZ format.
- Dominant spectral peaks are located at $\nu_0 \pm B/2$, rather than at $\nu_0 \pm B$.
- Considerable filtering of signal possible before it is launched into optical fiber, while retaining both sidebands.
- Figure 9.28 shows effects of filtering on the spectrum of a 40-Gb/s channel.
- Penalty was below 1.5 dB even for a 35-GHz filter, detuned off-center by an optimum amount (asymmetric filtering).
- By 2003, 128 channels at 40 Gb/s were transmitted over 1,280 km with this technique.

Impact of Asymmetric Filtering

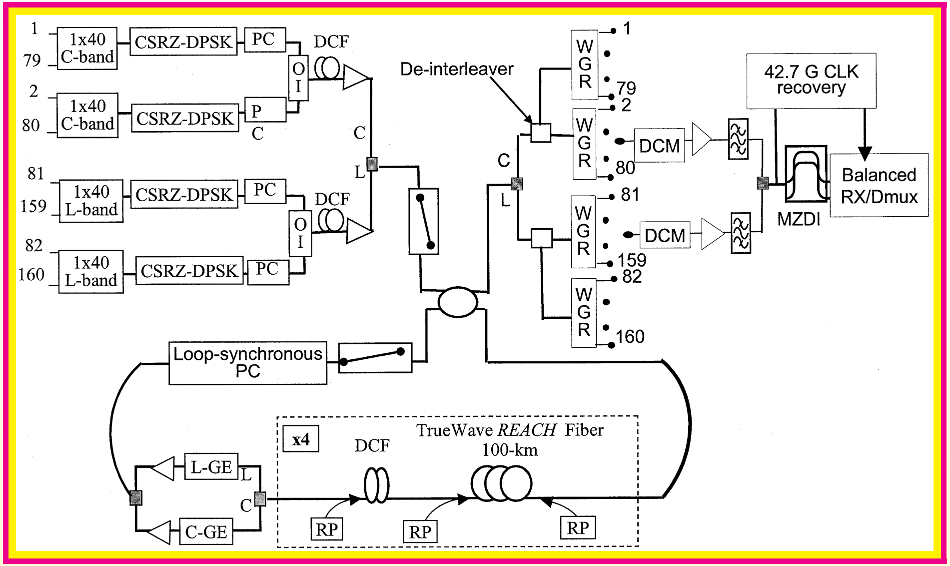


- (a) unfiltered case; (b) symmetric 68-GHz filter; (c) symmetric 35-GHz filter; (d) asymmetric 68-GHz filter; (e) asymmetric 35-GHz filter.

CSRZ-DPSK format

- In RZ-DPSK format, information is coded in optical phase but a pulse is present in all bit slots.
- One can combine the CSRZ with DPSK by changing phase of alternate pulses, in addition to the phase shift required for DPSK coding.
- This type of DPSK coding has proven to be quite useful for WDM systems.
- In a 2004 experiment, 160 channels at 42.7 Gb/s (capacity 6.4 Tb/s) were transmitted over 3200 km of fiber.
- Raman amplification was used with 100-km spacing between pump stations.

CSRZ-DPSK format



- Experimental setup for the CSRZ-DPSK system with 6.4-Tb/s capacity.
- Capacity–distance product exceeded 20 (Pb/s)-km in this experiment.

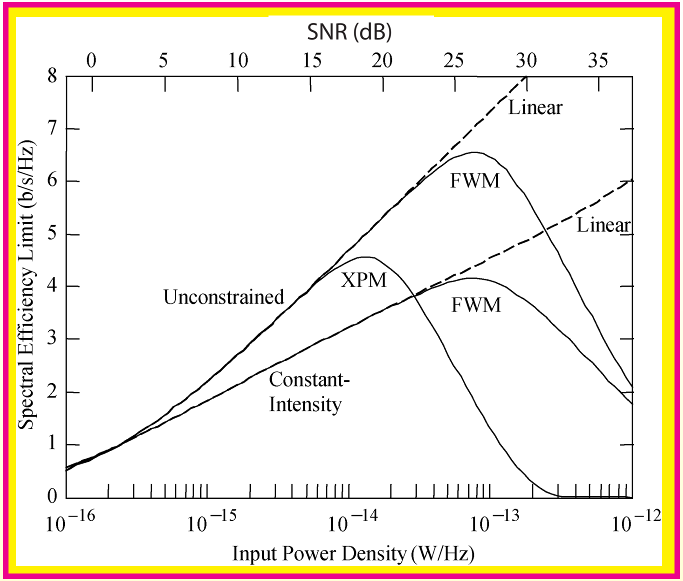
Ultimate Channel Capacity

- Question: Is it is possible to realize $\eta_s > 1$ (b/s)/Hz?
- Issue of channel capacity was first studied by Shannon.
- Channel capacity/Hz for a linear channel of bandwidth Δf_{ch} is given by

$$\eta_c = C_{\text{ch}}/\Delta\nu_{\text{ch}} = \eta_s \log_2(1 + \text{SNR}).$$

- It can be increased beyond 1 (b/s)/Hz without an upper bound.
- Optical fibers do not constitute a linear channel, and this results does not apply for them.
- Degradation caused by nonlinear effects limits η_c to a maximum value.

Ultimate Capacity



- Spectral efficiency as a function input power density.
- Unconstrained: Both the phase and intensity modulated.
- Nonlinear effects limit η_c to below 5 (b/s)/Hz.

Dispersion Fluctuations

- Zero-dispersion wavelength λ_0 of a fiber depends on its core diameter.
- It varies along the fiber randomly by a small amount.
- Variations in λ_0 manifest as changes in $D(\lambda)$ at channel wavelength.
- A second source of dispersion fluctuations is related to environmental changes.
- If temperature of the fiber changes at a given location, its local dispersion also changes because D depends on temperature.
- Such dynamic fluctuations are of concern for 40-Gb/s channels for which dispersion tolerance is relatively tight.

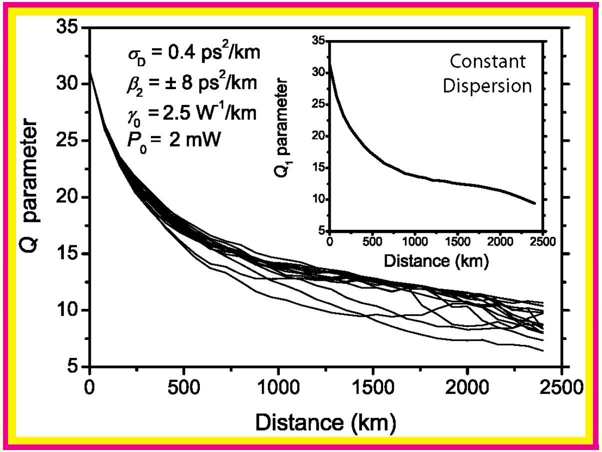
Modeling of Dispersion Fluctuations

- To study the impact of dispersion fluctuations on a WDM channel operating at 40 Gb/s, NLS equation is solved numerically.
- Dispersion fluctuations are included by writing

$$\beta_2(z) = \bar{\beta}_2(z) + \delta\beta_2(z).$$

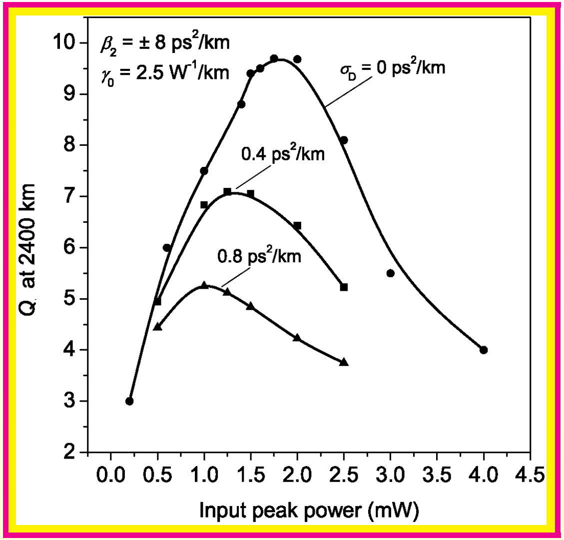
- $\bar{\beta}_2$ is the average value of local dispersion.
- $\delta\beta_2$ is a random variable assumed to have a Gaussian distribution with zero mean and standard deviation σ_D.
- Q factor changes in a random fashion for different realizations of dispersion distribution.
- BER of a WDM channel can change during a day because of temperature-induced changes in fiber dispersion.

Impact of Dispersion Fluctuations



- Q factor as a function of distance for 15 realizations.
- Dispersion map consisted of two 5-km sections with $\bar{\beta}_2 = \pm 8$ ps^2/km.
- Link losses are compensated every 80 km through distributed Raman amplification.

Impact of Dispersion Fluctuations

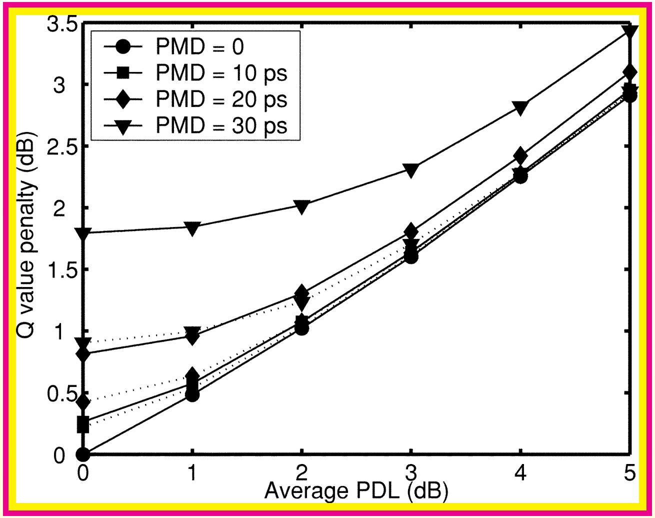


- Worst-case Q factor for a 40-Gb/s channel at a distance of 2400 km as a function of input peak power for three values of σ_D.
- In the absence of dispersion fluctuations, $Q \approx 9.5$ around 2 mW is large enough that the system can operate without FEC.

PMD and Polarization-Dependent Losses

- Fluctuations in the residual birefringence of fibers change the state of polarization (SOP) in a random fashion.
- They also distort optical pulses because of random changes in the speeds of the orthogonally polarized components.
- In a realistic WDM system, one should also consider the effects of polarization-dependent loss (PDL) associated with optical components.
- When optical amplifiers are used, polarization-dependent gain (PDG) of such amplifiers can also degrade a WDM system.
- Considerable attention has been paid to evaluate impact of PMD, PDL, and PDG.

PMD and PDL Effects



- *Q*-factor penalty as a function of the average value of PDL for several values of PMD.
- Dotted lines show improvement with PMD compensation.
- Simulations performed for a 10-Gb/s RZ channel operating over 4,000 km with 100-km fiber spans.

Wavelength Stability

- WDM systems employ semiconductor lasers as an optical source.
- Wavelength is set by a built-in grating ($\lambda_c = 2\bar{n}\Lambda$).
- λ_c can only change if $\bar{n}$ changes.
- λ_c changes with temperature at a rate of 0.1 nm/$^\circ$C.
- Similar changes can occur with the aging of lasers.
- Such wavelength changes become critical for dense WDM systems in which channel spacing can be below 25 GHz.
- Carrier frequencies of channels should be stable to within 1 GHz.
- Maximum allowed wavelength drift during laser lifetime is 10 pm.

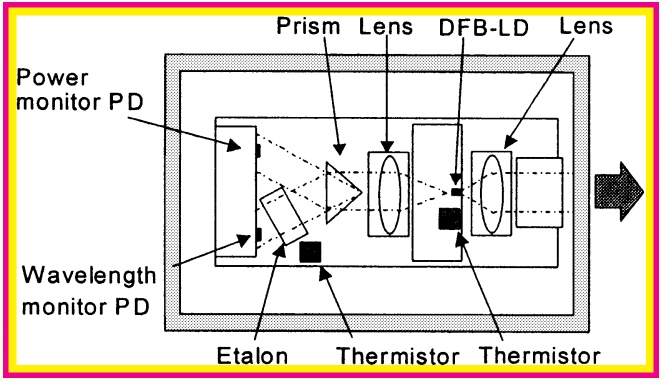
Wavelength Stability

- DFB lasers stabilize chip temperature to 1°C by integrating a thermoelectric cooler within the laser package.
- It provides sufficient wavelength stability for WDM systems with a channel spacing of 100 GHz or more.
- A thermoelectric cooler is not sufficient when channel spacing is 50 GHz or less.
- A number of techniques have been developed for stabilizing laser wavelength to meet the requirement of dense WDM systems.
- One technique employs molecular gases (ammonia or krypton) to lock laser frequency to a resonance frequency.
- Another technique uses optogalvanic effect with a gas.

Wavelength Stability

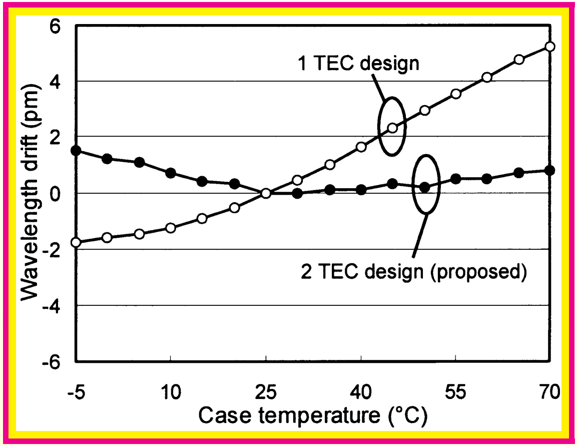
- Use of a molecular gas is not practical.
- What one really needs is a comb of uniformly spaced and well-stabilized frequencies.
- A Michelson interferometer can provide a set of equally spaced reference frequencies.
- A filter with a comb-like periodic transmission spectrum can also be used.
- In practice, a wavelength monitor is integrated within the laser module to stabilize λ to within 5 pm.
- A Fabry–Perot étalon is used for a frequency comb.
- To ensure that the comb does not drift, a separate thermoelectric coolers is used for the Fabry–Perot cavity.

Wavelength Monitoring



- Light from the back facet of the DFB laser is split into two branches using a prism.
- A Fabry–Perot étalon serves as a wavelength reference.
- It is designed such that one of its transmission peaks occurs precisely at the wavelength at which the laser is designed to operate.

Wavelength Stability

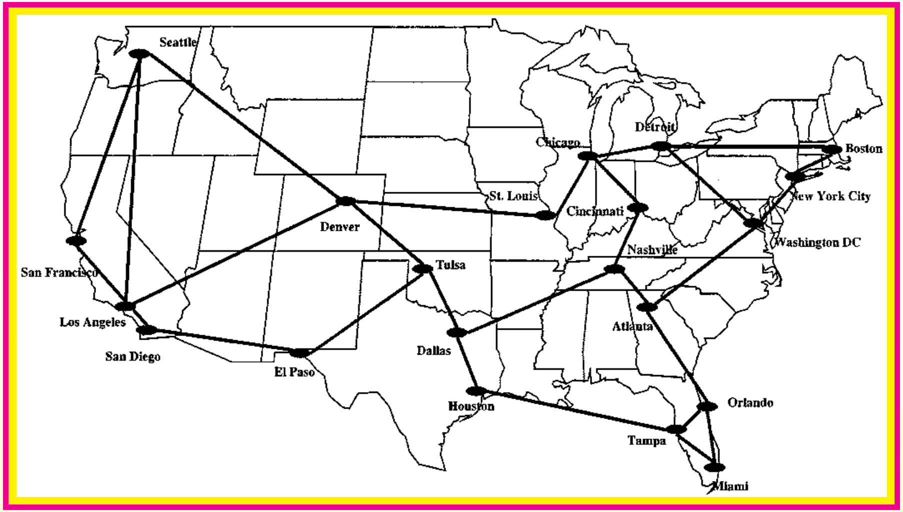


- Measured wavelength drift as a function of module temperature at 20-mW output power.
- Laser wavelength changes by less than 2 pm over a temperature range from -5 to 70°C when two thermoelectric coolers are used.
- Such devices are suitable for WDM systems.

Chapter 10
Optical Networks

- Network Architecture and Topologies
- Network Protocols and Layers
- Wavelength-Routing Networks
- Packet-Switched Networks
- Other Routing Techniques
- Distribution and Access Networks

Wide-Area Networks

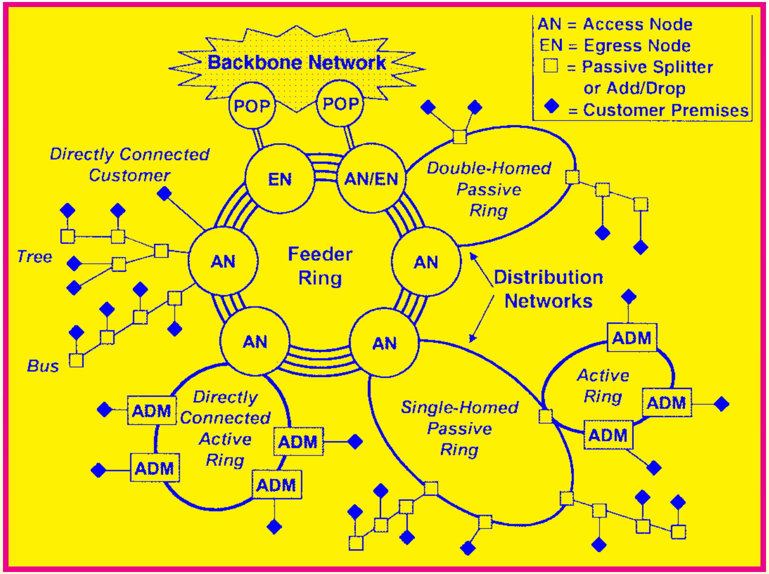


- An example of a wide-area network designed with the hub topology.
- Hubs are located in major cities.
- Such networks are also called mesh networks.

Wide-Area Networks (WANs)

- Hubs or nodes (located in large metropolitan areas) contain electronic switches.
- Switches connect any two nodes by creating a "virtual circuit" between them.
- Creation of a virtual circuit between two arbitrary nodes requires switching at one or more intermediate nodes.
- This scheme is referred to as circuit switching.
- An alternative scheme, used for the Internet, is known as *packet switching*.
- It routes packets through the TCP/IP protocol.

Metropolitan-Area Networks (MANs)



- Schematic of a MAN with a ring topology.
- MAN is connected to a WAN at egress nodes (EN).
- MAN is connected to LANs at access nodes (AN). ADM stands for add–drop multiplexer.

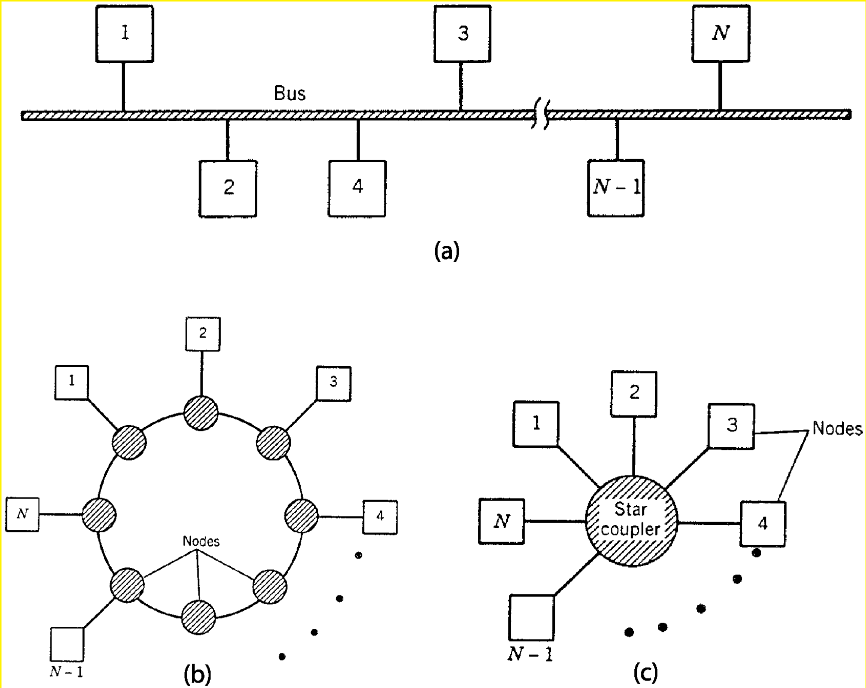
Metropolitan-Area Networks (MANs)

- Several MANs can be interconnected with a ring to form a regional network.
- Regional rings provide protection against failures.
- Protection fibers in each ring ensure that an alternate path between any two nodes can be found if a single point-to-point link fails.
- In a metro ring, traffic flows at a modest bit rate (2.5 Gb/s).
- To reduce the cost, a coarse WDM technique is employed.
- Most metro networks still employ electronic switching.
- All-optical switching remains the ultimate goal.

Local-Area Networks (LANs)

- LANs interconnect a large number of users within a local area (e.g., a town or a university campus)
- Any user can transmit data to any other user at any time.
- Access networks used in a subscriber loop (or a local loop) also fall into this category.
- As transmission distances are relatively short ($<$10 km), fiber losses as well as the dispersive and nonlinear effects occurring inside fibers are not of concern for LANs.
- Motivation behind using optical fibers is a much larger bandwidth offered by them compared with a coaxial cable.

Network Topologies



- Bus, ring, and star topologies employed for LANs.

Network Topologies

- In the case of ring topology, a token is passed around the ring for nodes to extract or append data.
- In the case of star topology, all nodes are connected to the star coupler at a central location.
- Star coupler distributes data from each node to all nodes.
- Signal power reaching decreases as the number of nodes increases.
- This type of loss is known as distribution loss.
- Some LANs distribute information without requiring a two-way connection (cable television).
- CATV networks employ bus topology. A single optical fiber carries multiple video channels through subcarrier multiplexing.

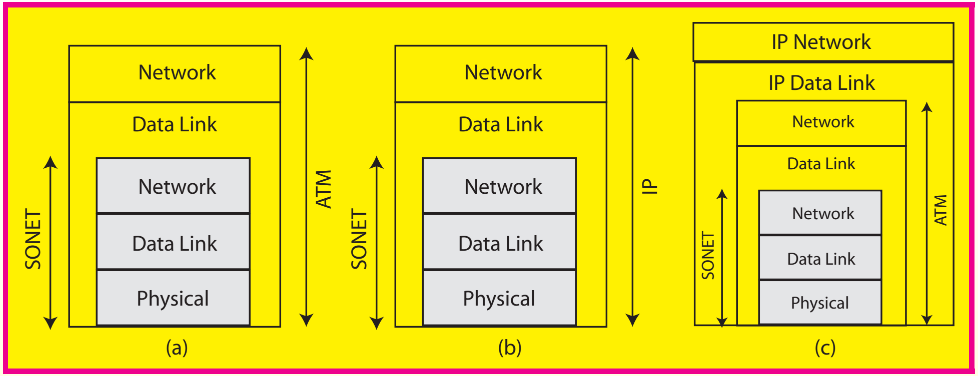
Distribution Losses

- A problem with bus topology is that distribution losses increase exponentially with the number of taps.
- Such losses limit the number of subscribers that can be served by a single optical bus.
- Even when fiber losses are neglected, the power available at the Nth tap is given by

$$P_N = P_T C[(1-\delta)(1-C_f)]^{N-1}.$$

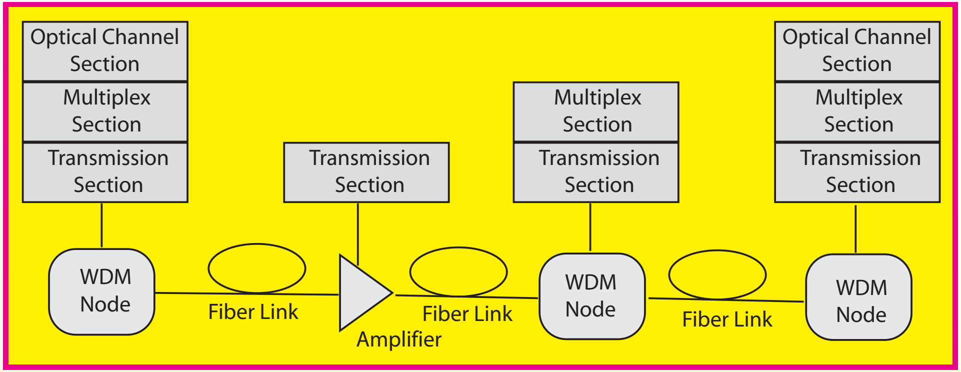
- P_T is the transmitted power, C_f is the fraction of power coupled out at each tap, and δ accounts for insertion loss.
- If we use $\delta = 0.05$, $C_f = 0.05$, $P_T = 1$ mW, and $P_N = 0.1$ μW, N should not exceed 60.

Network Protocols and Layers



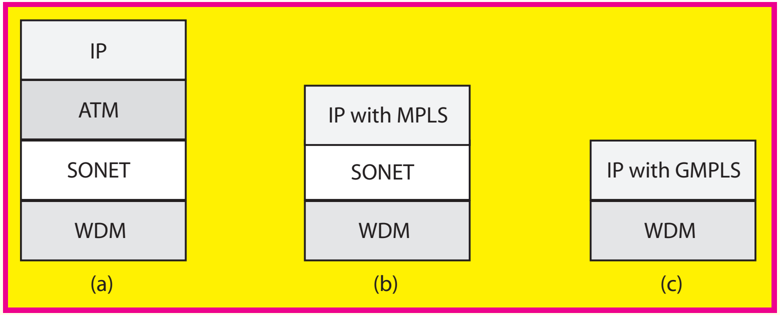
- Layered architecture for SDH networks:
  - ⋆ (a) ATM over SONET
  - ⋆ (b) IP over SONET,
  - ⋆ (c) IP over ATM.
- ATM protocol employs 53-byte packets (5-byte header).

Evolution of WDM Networks



- WDM systems employ a new layer known as the *optical layer*.
- It consists of three sections known as the transmission section, multiplex section, and optical channel section.
- Not all sections need to be present at every component.

Evolution of WDM Networks



- Evolution of modern WDM networks through MPLS and GMPLS schemes: (a) IP over ATM; (b) IP over SDH; (c) IP over WDM.
- MPLS stands for multiprotocol label switching.
- MPLS deals with multiple protocols through a label attached to each packet.
- It can transport both the ATM and IP packets across a packet-switched network.

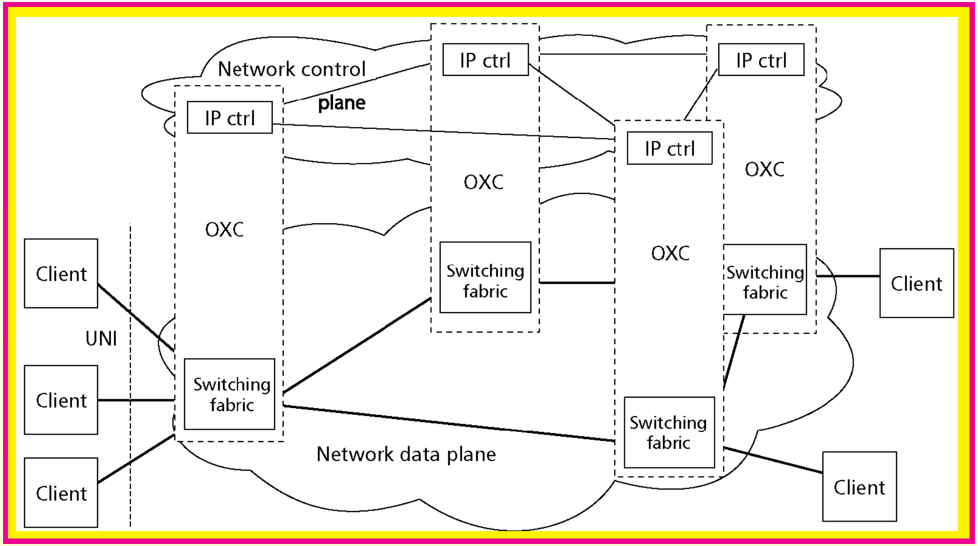
Multiprotocol Label Switching

- MPLS works by encapsulating each packet with an MPLS header containing one or more labels.
- Labels are used to specify a forwarding equivalence class in which all packets with the same label are treated in the same way.
- Packets are forwarded along a label-switched path (an MPLS tunnel) that constitutes a virtual circuit.
- Entry point of the MPLS tunnel is at ingress router and the exit point is at egress router.
- At each intermediate router, based on the contents, label is either removed or swapped with a new label.
- Packet is then forwarded to next transit router along MPLS tunnel.

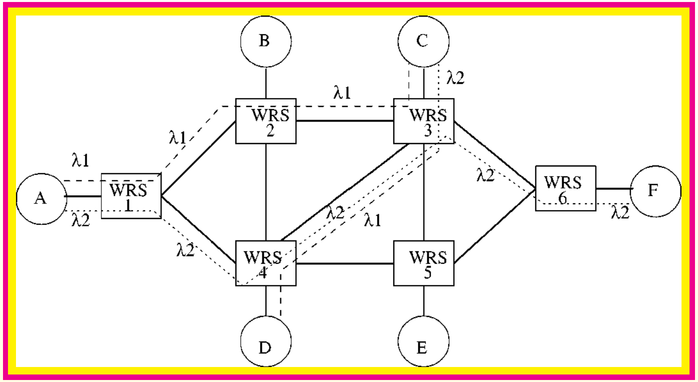
Network Planes

- Functions performed by a network can be grouped into three planes: transport plane, control plane, and management plane.
- Transport plane focuses on the transport of data across a network. (also called the data plane).
- It should provide bidirectional flow of information among various nodes, while maintaining signal quality.
- In the case of WDM networks, transport plane also performs all-optical routing, detects faults, and monitors signal quality.
- Role of a control plane is to control electronically how optical switching is performed in the transport plane.
- Management plane deals with the management of the whole network.

Network Planes



Wavelength-Routing Networks



- Schematic of a six-node network.
- Wavelength-routing switches (WRS) are used to establish lightpaths among various nodes using only two wavelengths.
- Dashed and dotted lines show the paths taken by the λ_1 and λ_2 channels, respectively.

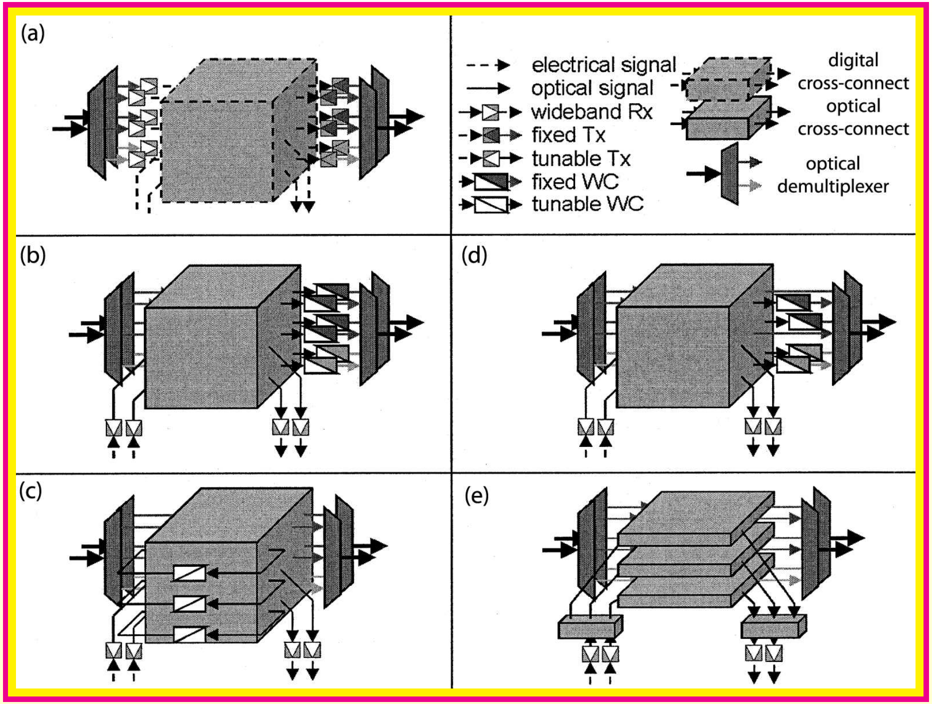
Wavelength Switching and Its Limitations

- In the absence of wavelength converters, a lightpath must have the same wavelength on across all nodes.
- This requirement is referred to as wavelength-continuity constraint.
- A second obvious constraint is that two lightpaths transported over the same physical fiber link must have different wavelengths.
- These two constraints make wavelength assignments across the network quite complex.
- It may not even be possible to connect all nodes with a unique lightpath.
- Design is simplified considerably if wavelength converters are employed within each OXC.

Wavelength Routing Schemes

- In general, two nodes can be connected with several lightpaths.
- Two schemes can be used for selecting an appropriate lightpath among various alternate routes.
- Fixed-alternate routing: Each router contains a routing table that assigns a priority number to potential routes.
- Router tries the route with highest priority. If this is not possible, it selects alternate routes until a valid lightpath is found.
- Adaptive routing: Lightpath is chosen dynamically, depending on the state of the network at the time decision is made.
- This approach computes the "cost" of each lightpath in terms of specific design objectives (efficient operation, optimum use of bandwidth, number of hops, etc.).

Optical Cross-Connects



- (a) Electronic switching; (b) Wavelength conversion at each node.
- (c) Shared conversion; (d) Partial conversion; (e) No conversion.

Limited Wavelength Conversion

- Number of wavelength converters required in (b) equals MN when node is designed to handle traffic on M fibers, each carrying N wavelengths.
- To reduce the hardware cost, wavelength converters are shared in a loop-back configuration in (c).
- In (d) a small number of wavelength converters used at each node (partial conversion).
- Limited wavelength conversion introduces a finite probability of wavelength blocking.
- This probability can be reduced if wavelength converters are made tunable over the entire bandwidth of the WDM signal.

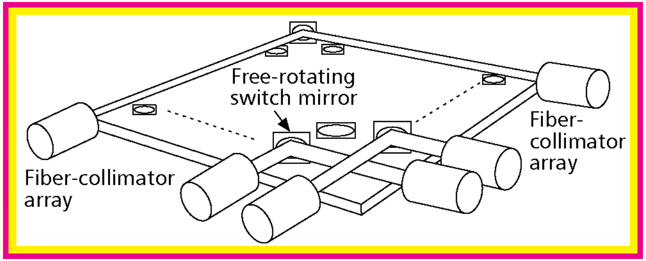
Wavelength-Selective OXCs

- wavelength-selective OXCs need no wavelength converters.
- Designed to distribute all input signals at a specific wavelength to a separate switching unit.
- Each unit consists of a $M \times M$ switching fabric that can be configured to route signals at a fixed wavelength in any fashion.
- Extra input and output ports can be added to allow dropping or adding of a local channel at that wavelength.
- They are transparent to both the format and bit rate of the WDM signal. They are also cheaper and help to reduce overall cost.
- These advantages are overshadowed by wavelength blocking.

Switching Technologies

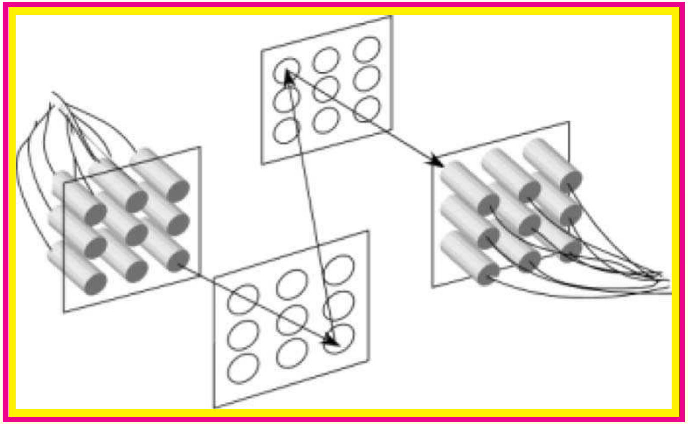
- All OXCs need a switching fabric capable of interconnecting a large number of input and output ports in an arbitrary fashion.
- Several technologies can be employed for this purpose.
  - ⋆ Electro-optic switches based on $LiNbO_3$ waveguides
  - ⋆ Thermo-optic switches based on silica waveguides
  - ⋆ Microscopic mirrors built with MEMS technology
  - ⋆ Bubble switches based on total internal reflection
  - ⋆ Liquid-crystal switches based on birefringence-induced polarization changes.

MEMS-Based Switching



- Schematic of a two-dimensional MEMS-based OXC.
- Microscopic mirrors are flipped to connect input and output fibers in an arbitrary fashion.
- Entire matrix of microscopic mirrors can be integrated on a silicon chip
- Switching time typically exceeds 5 ms for MEMS mirrors.
- Insertion losses remain close to 3 dB for a 16×16 switch with a chip size of 2×2 cm^2 (1-mm spacing between mirrors).

MEMS-Based Switching

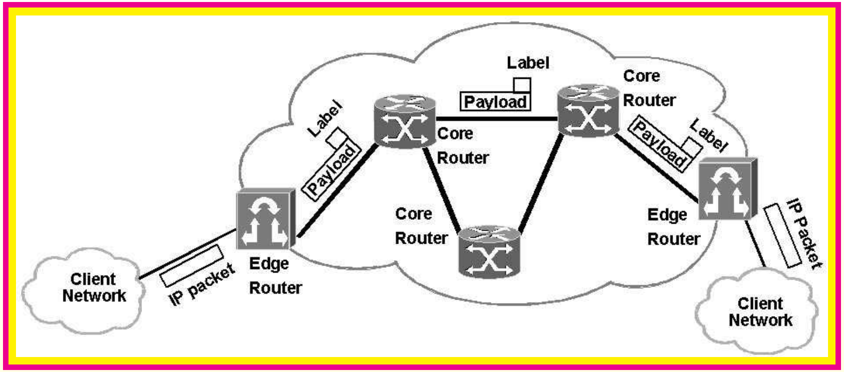


- 3D configuration preferred when number of input and output ports is relatively large.
- Only $2N$ mirrors are required in place of N^2 mirrors.
- Two MEMS devices with N mirrors interconnect N fibers by rotating mirrors in an analog fashion.

Packet-Switched Networks

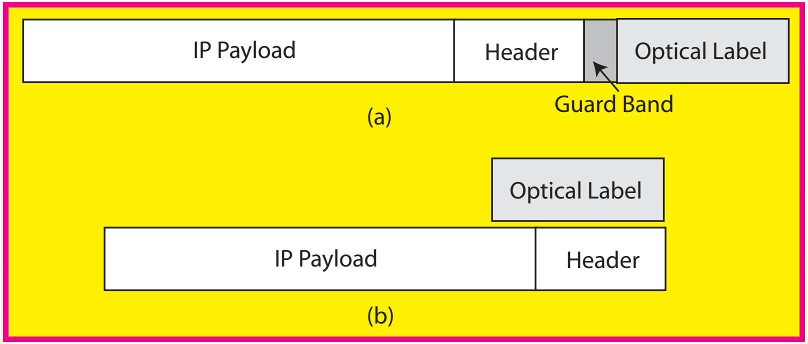
- Internet traffic consists of IP packets.
- In an all-optical Internet IP packets must be switched optically.
- Such packet-switched optical networks would make use of *optical routers*.
- A technique known as optical label swapping has been proposed for such routers.
- An optical label is coded with the routing information.
- This label is added on top of the electronic header associated with all IP packets.
- Contents of an IP packet are never converted into electric domain until the packet arrives at its destination.

Optical Label Swapping



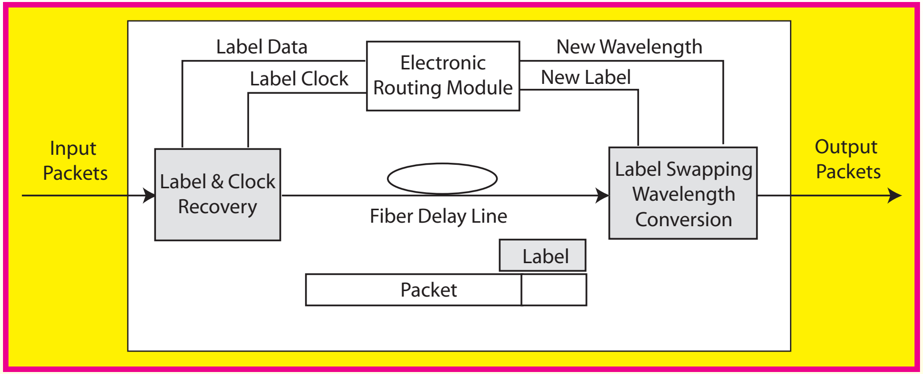
- Edge routers assign and remove the label.
- Core routers read the label, swap it with a new label, and forward it toward the next node.
- To perform routing and forwarding functions, each optical router makes use of an internal routing table that converts the IP addresses into optical labels at assigned wavelengths.

Techniques for Label Coding



- (a) serial label next to the IP header with a guard band.
- (b) label transmitted in parallel through subcarrier multiplexing.
- A microwave subcarrier at a frequency higher than the packet bit rate (>12 GHz for 10-Gb/s channels) is used to transport the label.
- No guard band is necessary in this case.
- Label can be as wide as the packet itself. This feature allows the use of a much lower bit rate for the label.

Design of Core Routers



- Label-processing module (first gray box) uses ∼1% of signal power to decode the label and recover the clock.
- Remaining signal is passed through an optical delay line to ensure that the packet reaches the second gray box in time.
- Label and the clock are sent to the cental routing module, where a routing table is used to find the next node.