

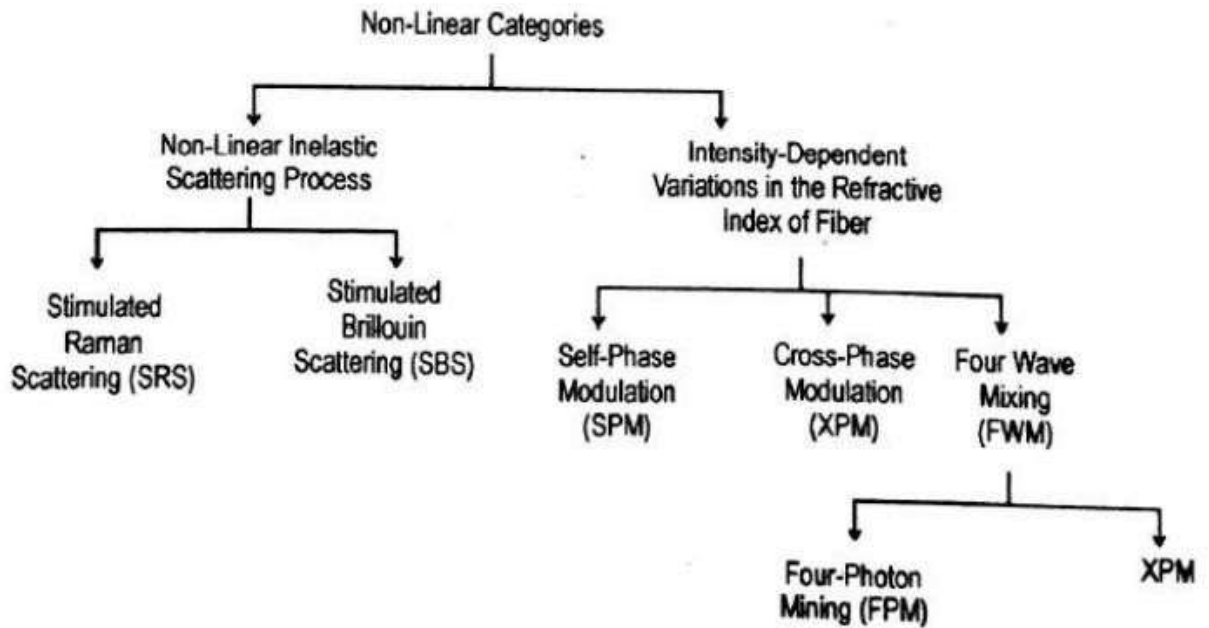
Non Linear Effect on Network Performance

Important Challenges in Designing Non Linear Networks:

- Transmission of the different wavelength channel at the highest possible bit rate.
- Transmission over the longest possible distance with the smallest number of optical amplifier.
- Network architectures that allow simple and efficient operation, control and management.

The Various Signal Impairment Effect are as Follows

- Group Delay Dispersion (GVD)**, Which limits the bit rate by temporally spreading a transmitted optical pulse, dispersion induced pulse spreading can be minimized by WDM networks operation in a low dispersion window such as 1310 nm and 1550 nm.
- Non-uniform gain across the desired wavelength range of EDFAs in WDM links.
- Polarization Mode Dispersion (PMD)**, Which arises from orthogonal polarization modes traveling at a slightly different speeds owing to fiber birefringence.
- Reflections from splices and connectors that can cause instabilities in laser sources. These can be eliminated by the use of optical isolators.
- Non-linear inelastic scattering processes, which are interactions between optical signal and molecular or acoustic vibrations in a fiber.
- Non-linear variations of the refractive index in a silica fiber that occur because the refractive index is dependent on intensity changes in the signal.



[Source: <http://img.brainkart.com>]

- A connection request between modes A and B is blocked if one of the H intervening fibers is full.

- The probability P_b' that a the connection request from A to B is blocked is the probability and fiber link with all wavelength F.

$$P_b' = 1 - (1 - \rho^r)^H \quad \dots (5.24)$$

- If q is the achievable utilization for a given blocking probability in a network with wavelength conversion.

$$q = [1 - (1 - P'_b)^{1/H}]^{1/F} \approx \left(\frac{P'_b}{H}\right)^{1/F} \quad \dots (5.25)$$

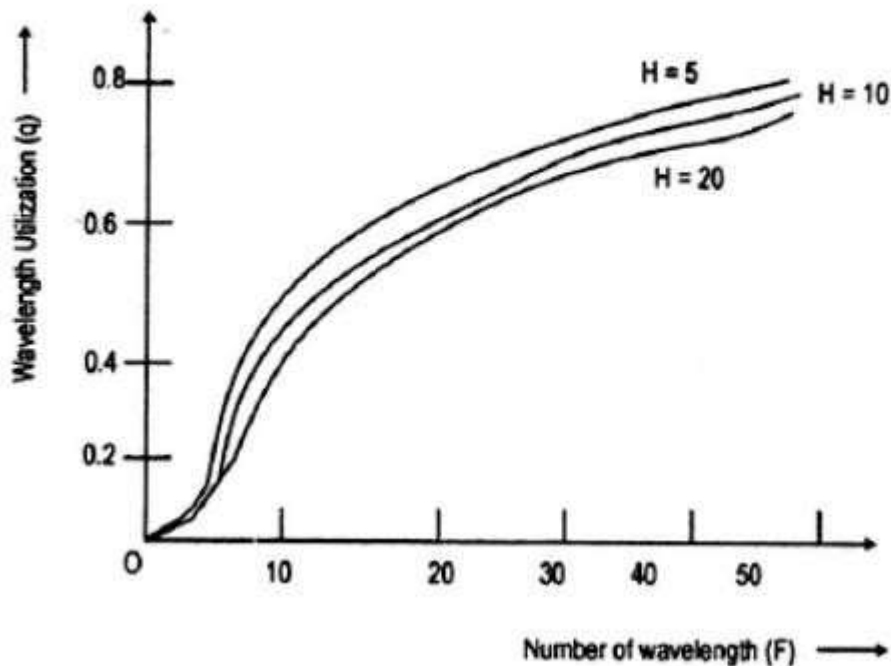


Figure 5.12 Wavelength utilization using wavelength conversion

[Source: <http://img.brainkart.com>]

- The effect of path length is small, and q rapidly approaches 1 as F becomes large.

A Network Without Wavelength Conversion

- A connection request between A and B can be honoured only if there is a free wavelength.
- The probability P_b that the connection request from A and B is blocked is the probability that each wavelength is used on at least one of the H links,

$$P_b = [1 - (1 - \rho)^H]^F \quad \dots (5.26)$$

- Letting P be the achievable utilization for a given blocking probability in a network without wavelength conversions,

$$P = 1 - (1 - P_b^{1/F})^{1/H} \approx -\frac{1}{H} \ln (1 - P_b^{1/F}) \quad \dots (5.27)$$

- Where the approximation holds for large values of H and for $P_{b1/F}$ not too close to unity.
- In this case, the achievable utilization is inversely proportional to the length of the path H between A and B.

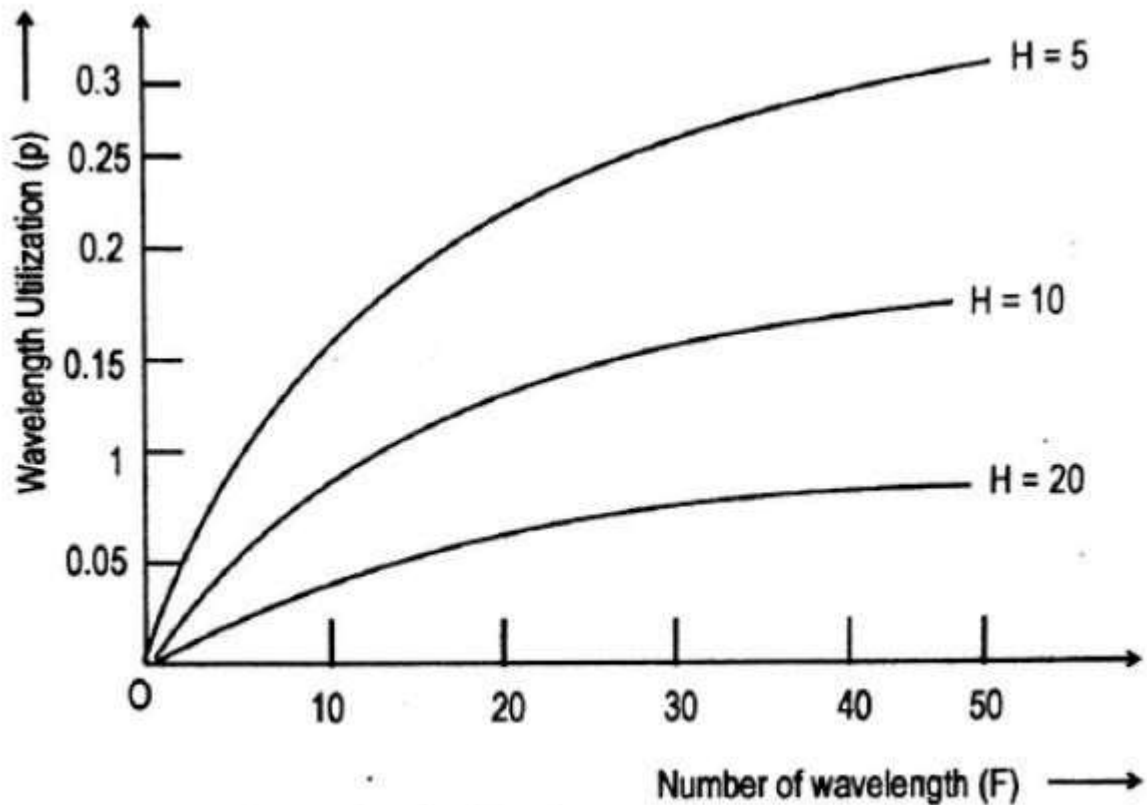


Figure 5.13 Wavelength utilization not using wavelength conversion

[Source: <http://img.brainkart.com>]

- Here the effect of path length (i.e., the number of links) is dramatic.

To Measure the Benefit of Wavelength Conversion

- The gain $G=q/P$ to be the increase in fiber or wavelength utilization for the same blocking probability.

- From equation (5.25) and (5.27). Setting $P'_b = p_b$ we have

$$G = q/P$$

$$G \equiv \frac{q}{P} = \frac{1 - [(1 - P_b)^{1/H}]^{1/F}}{1 - (1 - P_b^{1/F})^{1/H}}$$

$$\approx H^{1-1/F} \frac{P_b^{1/F}}{-\ln(1 - P_b^{1/F})} \quad \dots (5.28)$$

- G as a function of H=5, 10 and 20 links for blocking probability for $p_b=10^{-3}$.
- F increases, the gain increases, peaks at about H/2
- The gain slowly decreases, since large trunking networks are more efficient.

1. Effective Length and Area

- The non-linear process can be depend on the transmission length, the cross-sectional area of the fiber, and the optical power level in the fiber.
- **Effective Length** L_{eff} : Which takes into account power adsorption along the length of the fiber (i.e., optical power decays exponentially with length) is given by

$$L_{eff} = \frac{1}{P_0} \int_0^L P(z) dz = \int_0^L e^{-\alpha z} dz = \frac{1 - e^{-\alpha L}}{\alpha} \quad \dots (5.29)$$

- When there is a optical amplifier in a link, the effective length is the sum of the effective lengths of the individual spans between optical amplifiers.
- If the total amplified link length is L_A and the span length between amplifier is L, the effective length is

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \frac{L_A}{L} \quad \dots (5.30)$$

- The effects of non-linearities increase with the light intensity in a fiber. This light intensity is inversely proportional to the cross-sectional area of the fiber.
- As a rule of thumb, standard non-dispersion-shifted single mode fibers have effective area $A_{eff}=80\mu m^2$, dispersion-shifted fibers have effective area A_{eff} is $55\mu m^2$ and dispersion-compensating fibers have effective areas is $20\mu m^2$.

2. Stimulated Raman Scattering

- Stimulated Raman scattering is an interaction between light waves and the vibrational modes of silica molecules.
- If a photon with energy $h\nu_1$ is incident on a molecule having a vibrational frequency ν_{in} , the molecule can absorb some energy from the photon.
- In interaction, the photon is scattered, thereby attaining a lower frequency ν_2 a corresponding lower energy $h\nu_2$. The modified photon is called as stokes photon.
- The optical signal wave that is injected into a fiber is the source of the interacting photons, it is often called the pump wave, it supplies power from the generated wave.

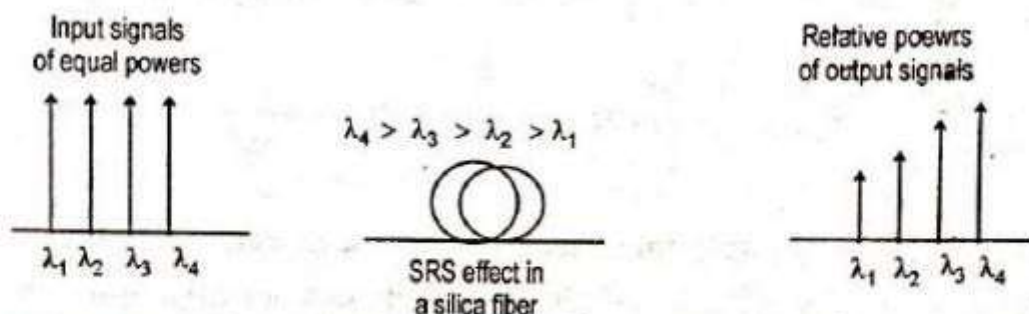


Figure 5.14 SRS Transfers optical power From Shorter Wavelength to Longer Wavelength

[Source: <http://img.brainkart.com>]

- SRS can severely limit the performance of a multichannel optical communication system by transferring energy from short-wavelength channels to neighboring higher-wavelength channels. This is a broadband effect that can occur in both directions.
- The effects of SRS, consider WDM system has N channel equally spaced in a 30 nm band centered at 1545 nm.
- Assume $f_{out}(j)$ is the fraction of power coupled from channel o to channel j

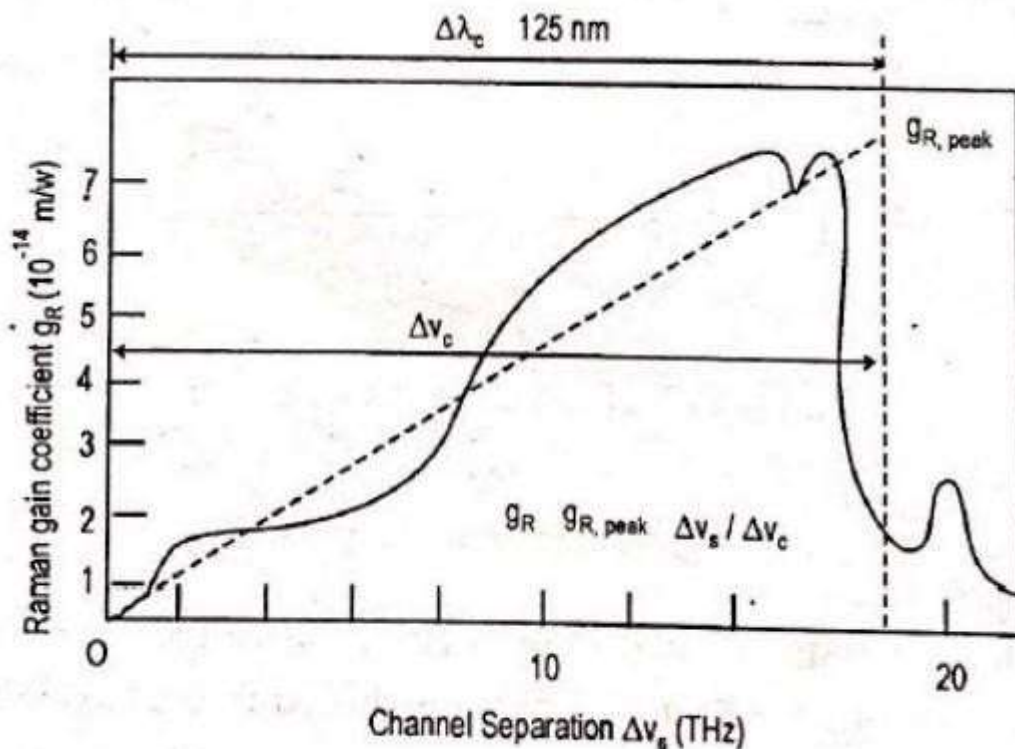


Figure 5.15 Wavelength Channel Separation

[Source: <http://img.brainkart.com>]

- The total fraction of power coupled out of 0 to all the other channel is

$$F_{out} = \sum_{j=1}^{N-1} F_{out}(j) = \sum_{j=1}^{N-1} g_{R,peak} \frac{j\Delta\nu_s}{\Delta\nu_c} \frac{PL_{eff}}{2A_{eff}}$$

$$= \frac{g_{R,peak} \Delta\nu_s PL_{eff}}{2\Delta\nu_c A_{eff}} \frac{N(N-1)}{2} \quad \dots (5.31)$$

- The power penalty for this channel is $-10 \log(1-F_{out})$

- To keep power penalty < 0.5 dB and $F_{out} < 0.1$ use equation (5.31) with $A_{eff} = 55 \mu m^2$, the criterion.

$$[NP] [N - 1] \Delta v_s L_{eff} < 5 \times 10^{-3} mW \cdot TH_s \cdot km \quad \dots (5.32)$$

where NP is the total power coupled into the fiber,

$(N - 1)\Delta v_s$ is the total occupied optical bandwidth.

L_{eff} is the effective length.

3. Stimulated Brillouin Scattering

- Stimulated Brillouin scattering arises when light waves scatter from acoustic waves.
- Scattered wave propagates principally in the backward direction in single-mode fibers. This backward light experiences gain from the forward-propagating signals.
- The frequency of the scattered light experiences a Doppler shift given by

$$\nu_B = 2n V_s / \lambda \quad \dots (5.33)$$

Where n is the index refraction, V_s is the velocity of sound in material.

- Interaction occurs Brillouin linewidth of $\Delta \nu_B = 20$ MHz at 1550 nm.
- For $V_s = 5760$ m/s in fused silica, the frequency of the backward propagating light at 1550 nm is shifted by 11 GHz (0.99 nm) from the original signal.
- In a long fiber chain containing optical amplifiers, there are optical isolators to prevent backward scattered signals from entering the amplifier.
- SBS threshold power P_{th} is defined to be the signal power at which the backward light equal the fiber-input power.

$$P_{th} \approx 21 \frac{A_{eff} b}{g_B L_{eff}} \left(1 + \frac{\Delta\nu_{source}}{\Delta\nu_B} \right) \quad \dots (5.34)$$

where A_{eff} is the effective cross-sectional area of propagating wave.

b is the polarization factor ($b = 1$ to 2).

L_{eff} is the effective length.

g_B is the Brillouing gain coefficient (4×10^{-11} m/w).

- The SBS threshold power increase as the source linewidth becomes larger.

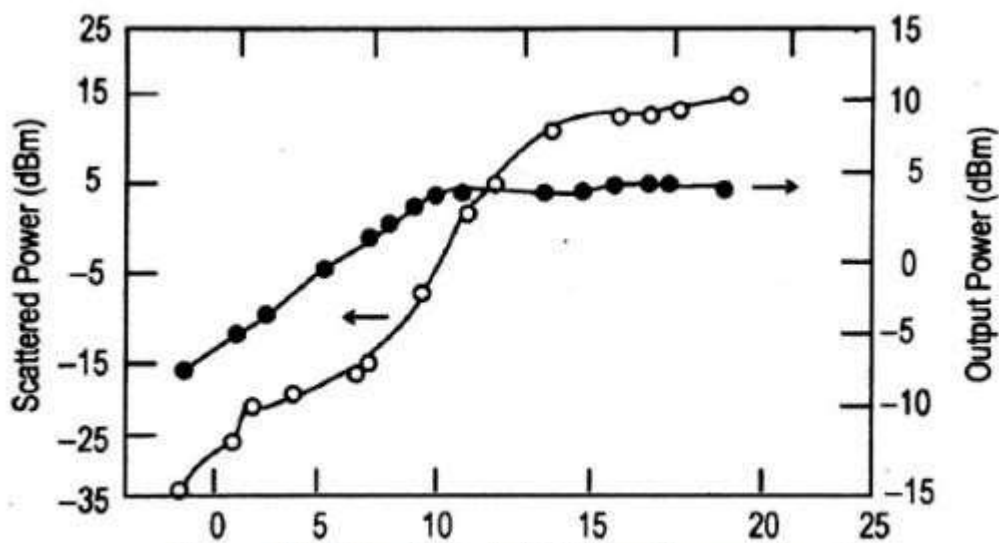


Figure 5.16 The Effect of SBS on Power Signal

[Source: <http://img.brainkart.com>]

- Several schemes are available for reducing the power penalty effects of SBS as follows:
 - Keeping the optical power per WDM channel below the SBS thresholds, for long-haul systems.
 - Increasing the linewidth of the source, since the gain bandwidth of SBS is very small. This can be achieved through direct modulation of the source.
 - Slightly dithering the laser output in frequency, at roughly tens of kilohertz. The dither frequency should scale as the ratio of the injected power to the SBS threshold.

4. Cross Talk

Crosstalk: it is defined as the feed through of one channel signal into another channel.

Types Of Crosstalk:

There are two types of crosstalk that can occur in WDM systems:

- (1) Intrachannel crosstalk
- (2) Interechannel crosstalk

(I) INTRACHANNEL CROSSTALK

It arises when interfering signal is at the same wavelength as the desired signal.

This effect is more severe than interchannel crosstalk, because the interference falls completely within the receiver bandwidth.

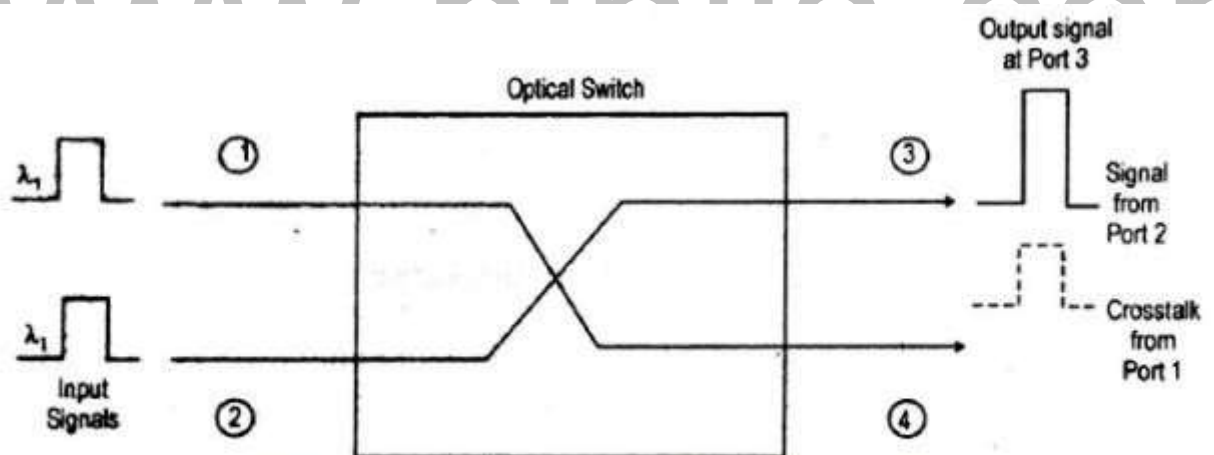


Figure 5.17 Origin of Inter channel Cross Talk

[Source: <http://img.brainkart.com>]

Two independent signals, each at a wavelength λ_1 , enter an optical switch.

This switch routes the signal entering port 1 to output port 4, and routes the signal entering port 2 to output port 3.

Within the switch, a spurious fraction of the optical power entering port 1 gets coupled to port 3, where it interferes with the signal from port 2.

(II) INTERCHANNEL CROSSTALK

It arises when an interfering signal comes from a neighbouring channel that operates at a different wavelength.

Power penalty of interchannel crosstalk is

$$\text{Penalty}_{\text{inter}} = -5 \log(1 - \epsilon) \quad \dots (5.43)$$

where ϵ is the a fraction of received crosstalk power.

Average crosstalk power $\epsilon_i P$, the factor is from equation (5.43)

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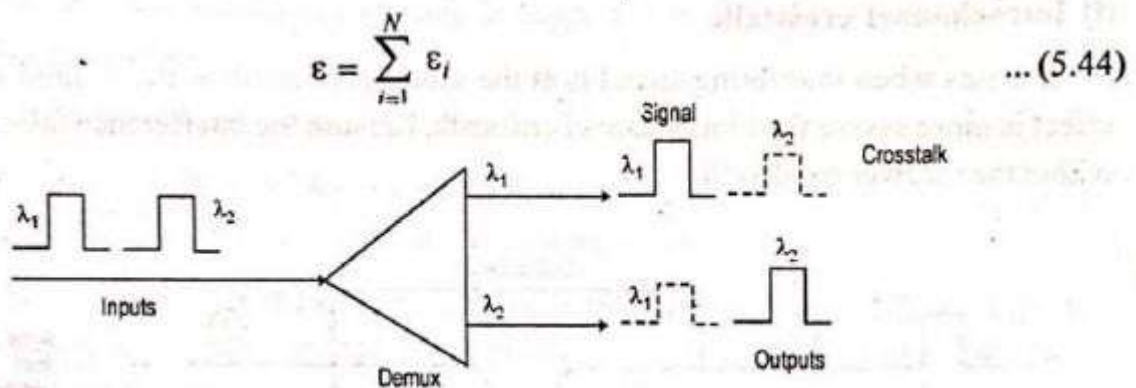


Fig. 5.32: Origin of interchannel crosstalk

[Source: <http://img.brainkart.com>]

Example, a 1-dB penalty arises when the intrachannel level is 38.7 dB below the signal level and for interchannel crosstalk is 16 dB below the signal.

Optical CDMA

The simplest configuration, CDMA achieves multiple access by assigning a unique code to each user.

To communicate with another node, user imprint their agreed upon code onto the data. The receiver can then decode the bit stream by locking onto the code sequence.

The principle of optical CDMA is based on spread-spectrum techniques.

The concept is to spread the energy of the optical signal over a frequency band that is much wider than the minimum bandwidth required to send the information.

Spreading is done by a code that is independent of the signal itself.

An optical encoder is used to map each bit of information into the high-rate (longer-code-length) optical sequence.

The symbols of the spreading code are called chips.

The energy density of the transmitted waveform is distributed more or less uniformly over the entire spread-spectrum bandwidth.

The set of optical sequences becomes a set of unique 'address codes or signature sequences' for the individual network users.

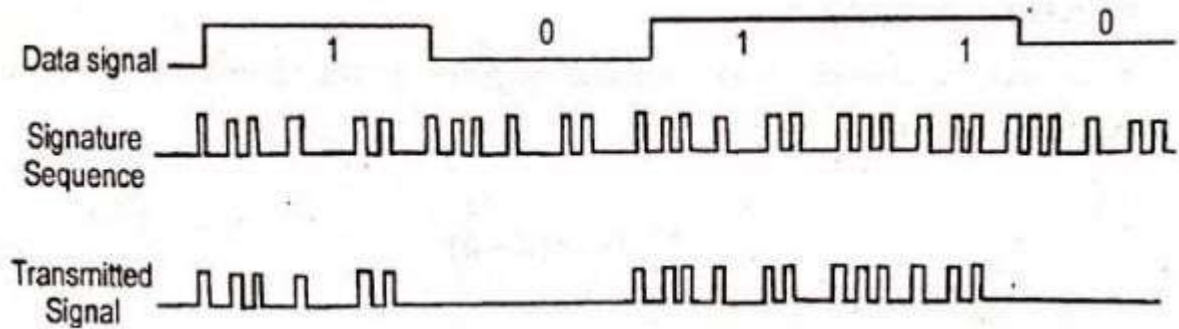


Figure 5.20 Six Chip optical CDMA Encoding Scheme

[Source: <http://img.brainkart.com>]

The signature sequence contains six chips. When the data signal contains 1 data bit, the six-chip sequence is transmitted, no chips are sent for a 0 data bit.

Time-domain optical CDMA allows a number of users to access a network simultaneously, through the use of a common wavelength.

Both asynchronous and synchronous optical CDMA techniques. In synchronous accessing schemes follow rigorous transmission schedules, they produce more successful transmission (higher throughputs) than asynchronous methods where network access is random and collisions between users can occur.

An optical CDMA network is based on the use of a coded sequence of pulses.

The setup consists of N transmitter and receiver pairs interconnected in a star

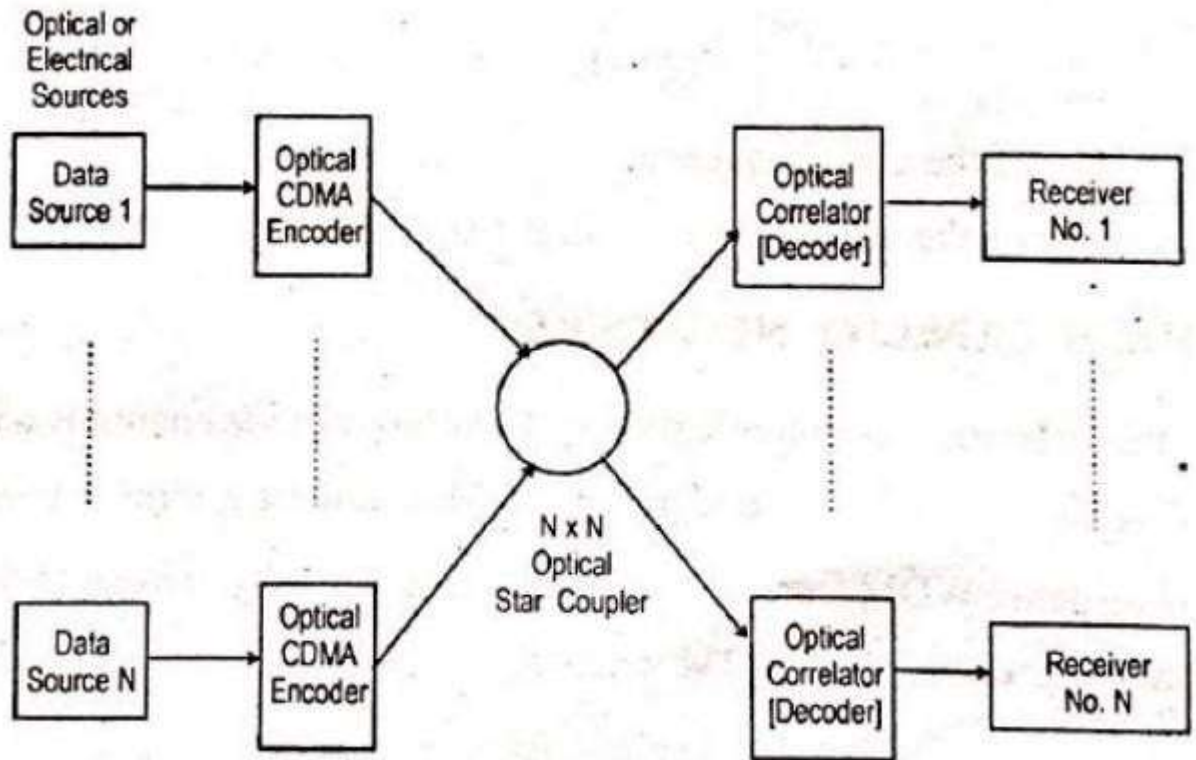


Figure 5.21 Optical CDMA Network Based on Using a Coded Sequence Pulse

[Source: <http://img.brainkart.com>]

To send information from node j to node k , the address code for node k is impressed upon the data by the encoder at node j .

At the destination, the receiver differentiates between codes by means of correlation detection.

Each receiver correlates its own address $f(n)$ with the received signal $s(n)$. The receiver output $r(n)$ is

$$r(n) = \sum_{k=1}^N s(k) f(k-n) \quad \dots (5.57)$$

If the received signal arrives at the correct destination, then $s(n)=f(n)$.

Equation (5.57) represents an autocorrelation function, if $s(n)$ not equal to $f(n)$ the equation (5.57) represents a cross-correlation function.

For a receiver to be able to distinguish the proper address correctly, it is necessary to maximize the autocorrelation function and minimize the cross-correlation function.

Prime-sequence codes and optical orthogonal codes (OOCs) are the commonly used spreading sequences in optical CDMA systems.

An OOC systems the number of simultaneous user an is bounded by

$$N \leq \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor \quad \dots (5.58)$$

Ultra High Capacity Networks:

Advance of optical communication systems has provide channels with enormous bandwidth at least 25THz and dense WDM technology, ultrafast optical TDM.

To using dense WDM techniques to increase the capacity of long-haul transmission link and ultrafast optical TDM schemes.

These are particularly attractive in LAN or MANs

TDM Schemes To Shared-Media Local Networks have Two Methods:

- (1) Bit-interleaved TDM.
- (2) Time-slotted TDM.

1. Ultra High Capacity WDM Networks

Two popular approaches are used to achieve increased capacity.

(a) to widen the spectral bandwidth of EDFAs from 30 to 80 nm, by using broadening techniques.

Increasing the capacity of a WDM link is to improve the spectral efficiency of the WDM signals.

Most of the demonstrations use a rate of 20 Gb/s for each individual wavelength to avoid non-linear effects.

Examples are,

(1) A 50-channel WDM system operating at an aggregated 1-Tb/s rate over a 600 km link.

(2) A 132-channel WDM system operating at an aggregated 2.6 Tb/s rate over a 120-km/link.

2. Bit-Interleaved Optical TDM

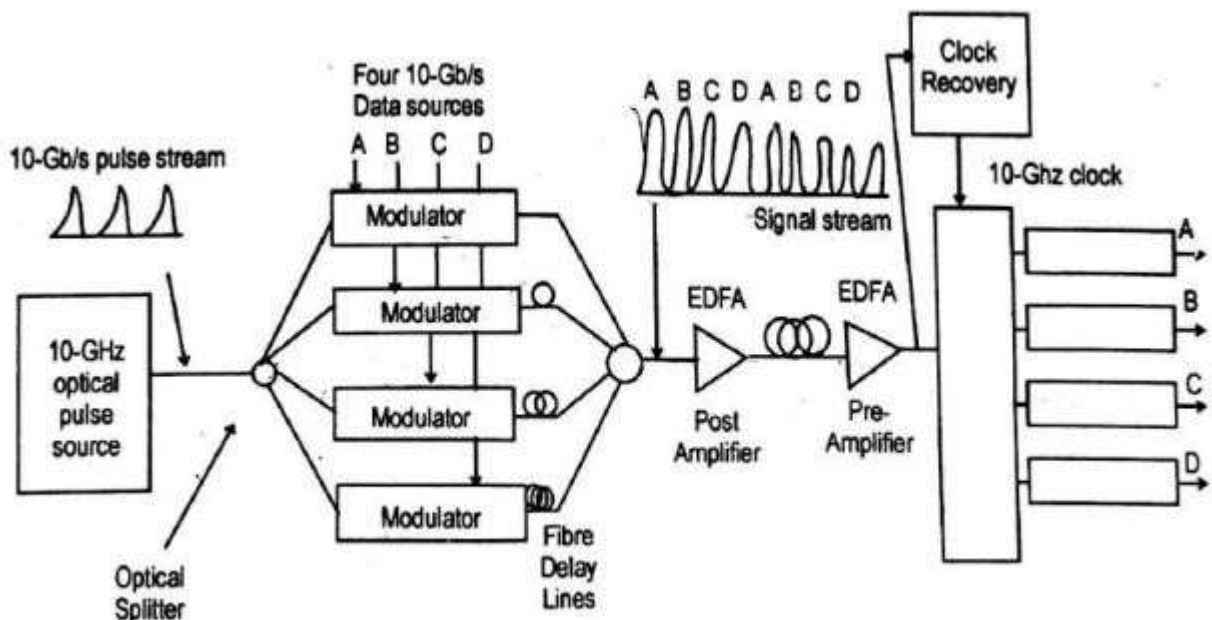


Figure 5.22 Ultrafast Point – Point Transmission System Using Optical TDM

[Source: <http://img.brainkart.com>]

Repetition rate typically ranges from 2.5 to 10 Gb/S, which corresponds to the bit rate of the electric data tributaries feeding the system.

An optical splitter divides the pulse train into N separate streams.

The pulse streams is 10 Gb/S and $N=4$, each of these channels is then individually modulated by an electrical tributary data source at a bit rate B .

The modulated outputs are delayed individually by different fractions of the clock period, and are then interleaved through an optical combiner to produce an aggregate bitrate of NXB .

Optical post amplifier and preamplifier are generally included in the link to compensated for splitting and attenuation loss.

At the receiving end, the aggregate pulse stream is demultiplexed into the original N independent data channels for further signal processing.

A clock-recovery mechanism operating at the base bit rate B is required at the receiver to drive and synchronize the demultiplexer.

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Solitons

Group velocity dispersion (GVD) causes most pulses to broaden in time as they propagate through an fiber.

A 'solitons' are pulses that travel along the fiber without change in shape or amplitude or velocity.

Soliton, takes advantage of non-linear effects in silica, particularly self phase modulation (SPM) resulting from the Kerr non-linearity, to overcome the pulse-broadening effects if GVD.

The term "soliton" refers to special kinds of waves that can propagate undistorted over long distances and remain unaffected after collision with each other.

In an optical communication system, solitons are very narrow, high intensity optical pulses that retain their shape through the interaction of balancing pulse dispersion with the non-linear properties of an optical fiber.

In an relative effects of SPM and GVD are controlled just right, and the appropriate pulse shape is chosen, the pulse compression routing from SPM can exactly offset the pulse broadening effect of GVD.

Fundamental Solitons- The family of pulse that do not change in shape are called fundamental solitons.

1. SOLITONS PULSE

When a pulse transverse a medium with a positive GVD parameter β_2 for the constituent frequencies, the leading part of the pulse is shifted toward a longer wavelength (lower frequencies) so that the speed in that portion increases.

In the trailing half, the frequency arises. So the speed decreases. This causes the trailing edge to be further delayed.

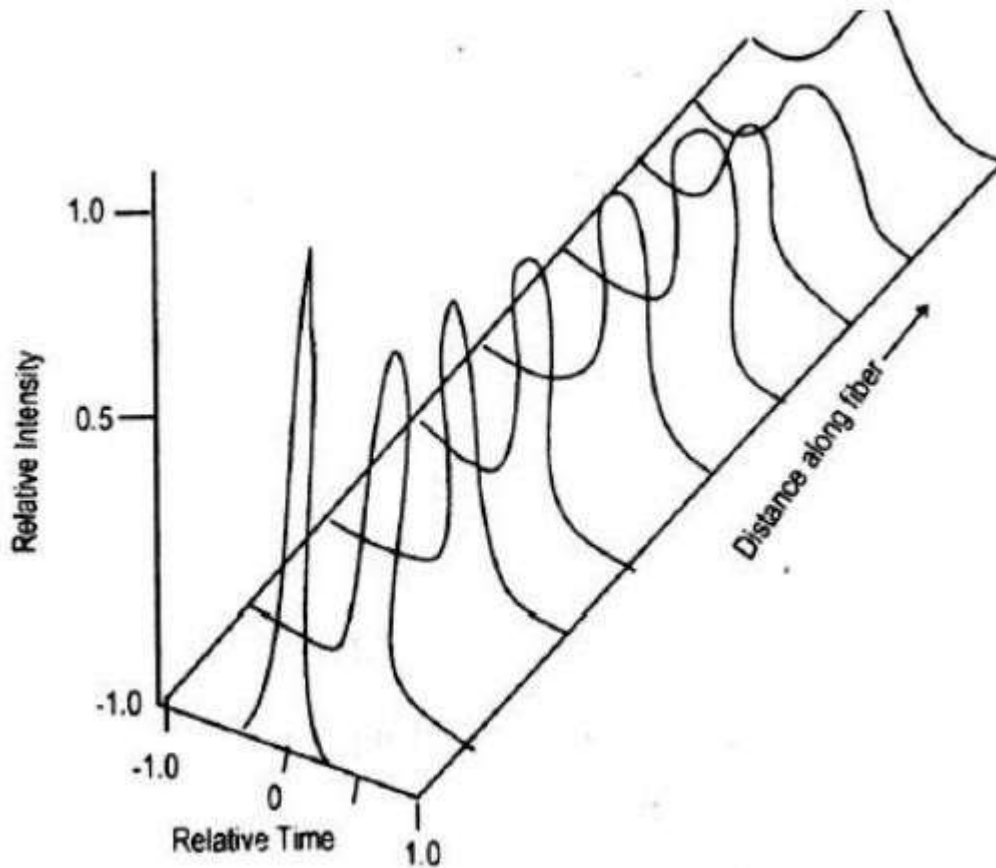


Figure 5.18 Temporal Change in a Narrow High Intensity Pulse

[Source: <http://img.brainkart.com>]

When a narrow high-intensity pulse traverse a medium with a negative GVD parameter for the constituting frequencies, GVD counteracts the chirp produced by SPM.

GND retards the low frequencies in the front end of the pulse and advances the high frequencies at the back.

The result is that the high-intensity sharply peaked soliton pulse changes neither its shape nor its spectrum as it travels along the fiber.

To derive the evolution of the pulse shape required for sodium transmission, one needs to consider the non-linear schrodinger (NLS) equation

$$-j \frac{\partial u}{\partial z} = \frac{1}{2} \frac{\partial^2 u}{\partial t^2} + N^2 |u|^2 u - j (\alpha/2) u \quad \dots (5.45)$$

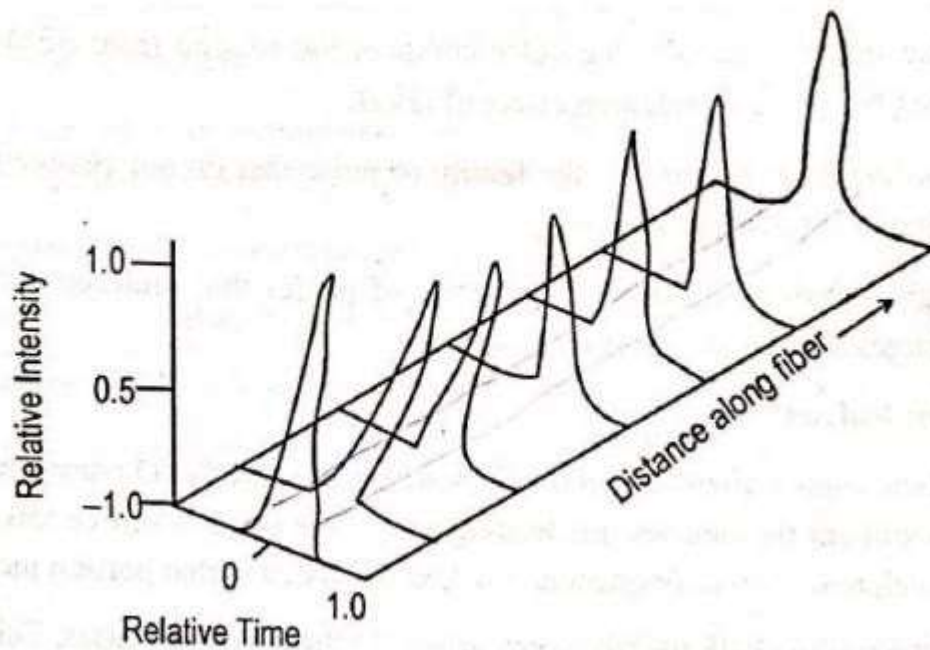


Figure 5.19 Characteristics of High Intensity Sharply Peaked Solitons Pulse

[Source: <http://img.brainkart.com>]

Special soliton units to eliminate scaling constants.

The Three Right-Hand Terms

- (1) The first term represents GVD effects of the fiber.
- (2) The second non-linear term denotes the fact that the refractive index of the fiber depends on the light intensity.

Through the self-modulation process, this physical phenomenon broadens the frequency spectrum of a pulse.

- (3) The third term represents the effects of energy loss or gain.

2. Solitons Parameters

Full-Width Half-Maximum (FWHM)

The full-width Half-maximum (FWHM) of a pulse is defined as the full width of the pulse at its half-maximum power level.

The FWHM T_s of the fundamental soliton pulse in normalized time is found from the relationship

$$\text{sech}^2(\tau) = \frac{1}{2}$$

where $\tau = \frac{\tau_s}{(2T_0)}$.

T_0 is the basic normalized time unit.

$$T_0 = \frac{T_s}{2 \cosh^{-1} \sqrt{2}} = \frac{T_s}{1.7627} \approx 0.567 T_s \quad \dots (5.49)$$

Dispersion Length (L_{disp})

The normalized distance parameter (also called dispersion length) L_{disp} is a characteristic length for the effects of the dispersion term.

L_{disp} is a measure of the period of a soliton

$$L_{disp} = \frac{2\pi c}{\lambda^2} \frac{T_0^2}{D} = \frac{1}{[2 \cosh^{-1} \sqrt{2}]^2} \frac{2\pi c}{\lambda^2} \frac{T_s^2}{D}$$

$$\approx 0.322 \frac{2\pi c}{\lambda^2} \frac{T_s^2}{D} \quad \dots (5.50)$$

where c is the speed of light,

λ is the wavelength in vacuum,

D is the dispersion of the fiber,

L_{disp} is measured in km.

The solution to equation (5.45) for the fundamental solution is given by

$$u(z, t) = \text{sech}(t) \exp(jz/2) \quad \dots (5.46)$$

Where $\text{sech}(t)$ is the hyperbolic secant function. This is a bell-shaped pulse.

The phase term $\exp(jz/2)$ in equation (5.46) has no influence on the shape of the pulse, the soliton is independent of z and hence is non-dispersive in the time domain.

For the NLS equation, to find the first-order effects of the dispersive and non-linear terms are just complementary phase shifts.

For a given by equation (5.46), these phase shifts are

$$d\phi_{\text{non-line}} = |u(t)|^2 dz = \text{sech}^2(t) dz \quad \dots (5.47)$$

For the non-linear process, and

$$d\phi_{disp} = \left(\frac{1}{2u} \frac{\partial^2 u}{\partial t^2} \right) dz = \left[\frac{1}{2} - \text{sech}^2(t) \right] dz \quad \dots (5.48)$$

Dispersion and non-linear phase shifts of a soliton pulse which sum is constant, which yields a common phase shift of $z/2$ for the entire pulse.

Since such a phase shift changes neither the temporal nor the spectral shape of a pulse, the soliton remains completely non-dispersive in both the temporal and frequency domain.

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SONET/SDH

- ✓ SONET is the TDM optical network standard for North America
- ✓ SONET is called Synchronous Digital Hierarchy (SDH) in the rest of the world
- ✓ SONET is the basic physical layer standard
- ✓ Other data types such as ATM and IP can be transmitted over SONET
- ✓ OC-1 consists of 810 bytes over 125 us; OC- n consists of $810n$ bytes over 125 us
- ✓ Linear multiplexing and de-multiplexing is possible with Add-Drop-Multiplexers
- ✓ The SONET/SDH standards enable the interconnection of fiber optic transmission equipment from various vendors through multiple-owner trunk networks.
- ✓ The basic transmission bit rate of the basic SONET signal is
- ✓ In SDH the basic rate is 155.52 Mb/s.

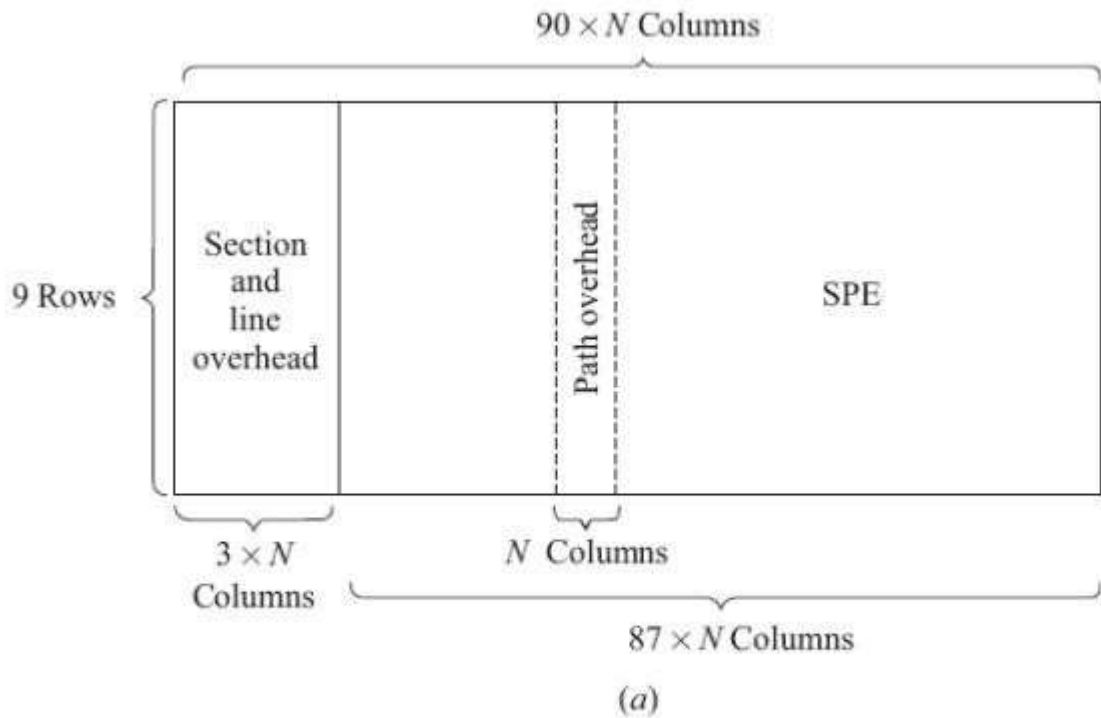


Figure 5.1 Basic formats of an STS-N SONET frame

[Source: <http://img.brainkart.com>]

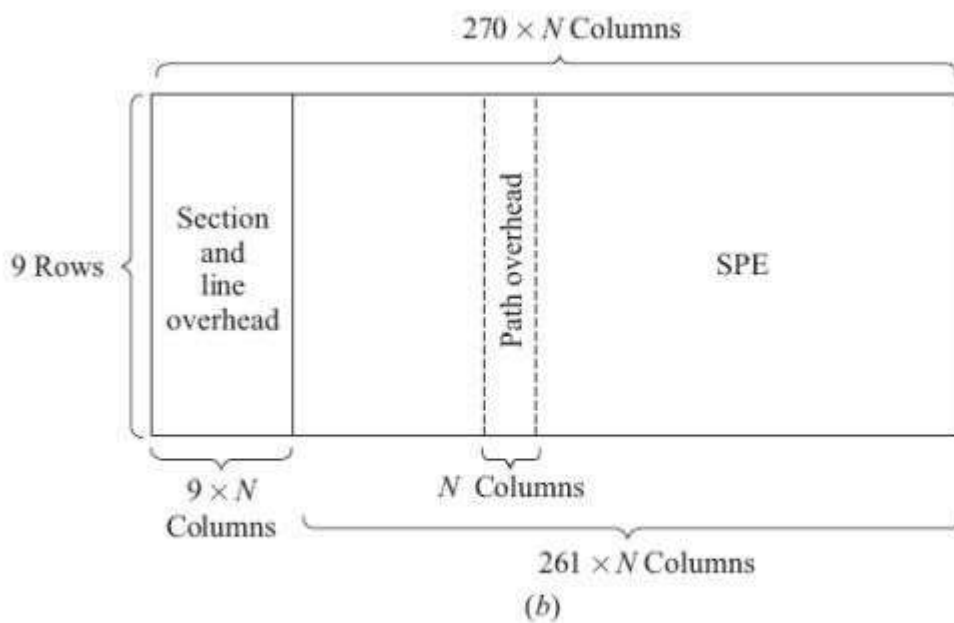


Figure 5.2 Basic formats of an STM-N SDH frame

[Source: <http://img.brainkart.com>]

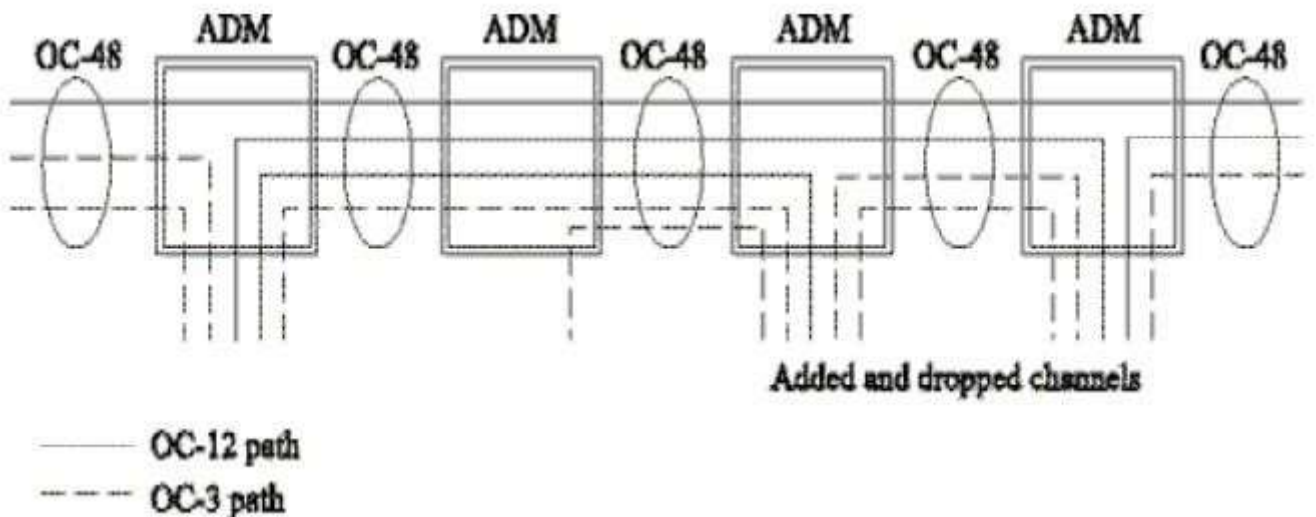
Common values of OC-N and STM-N:

- ✓ OC stands for optical carrier. It has become common to refer to SONET links as OC-N links.
- ✓ The basic SDH rate is 155.52 Mb/s and is called the synchronous transport module—level 1 (STM 1).

SONET level	Electrical level	SDH level	Line rate (Mb/s)	Common rate name
OC-N	STS-N	—	$N \times 51.84$	—
OC-1	STS-1	—	51.84	—
OC-3	STS-3	STM-1	155.52	155 Mb/s
OC-12	STS-12	STM-4	622.08	622 Mb/s
OC-48	STS-48	STM-16	2488.32	2.5 Gb/s
OC-192	STS-192	STM-64	9953.28	10 Gb/s
OC-768	STS-768	STM-256	39813.12	40 Gb/s

[Source: <http://img.brainkart.com>]

SONET Add Drop Multiplexers:



[Source: <http://img.brainkart.com>]

SONET ADM is a fully synchronous, byte oriented device, that can be used add/drop OC sub-channels within an OC-N signal

Ex: OC-3 and OC-12 signals can be individually added/dropped from an OC-48 carrier

SONET/SDH Rings:

- ✓ SONET and SDH can be configured as either a ring or mesh architecture
- ✓ SONET/SDH rings are *self-healing rings* because the traffic flowing along a certain path can be switched automatically to an alternate or standby path following failure or degradation of the link segment
- ✓ Two popular SONET and SDH networks:
 - 2-fiber, unidirectional, path-switched ring (2-fiber UPSR)
 - 2-fiber or 4-fiber, bidirectional, line-switched ring (2-fiber or 4-fiber BLSR)

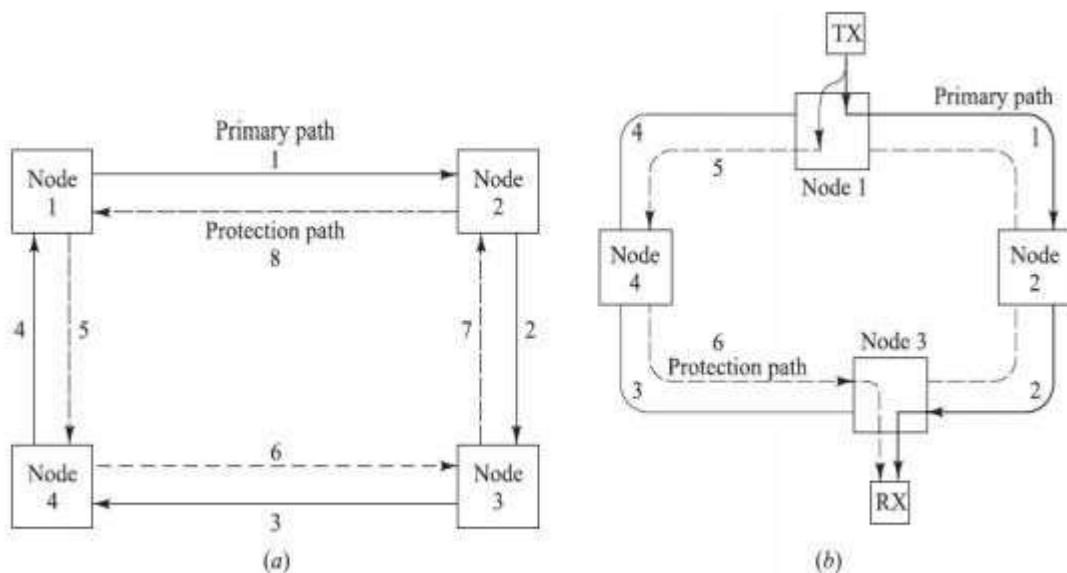
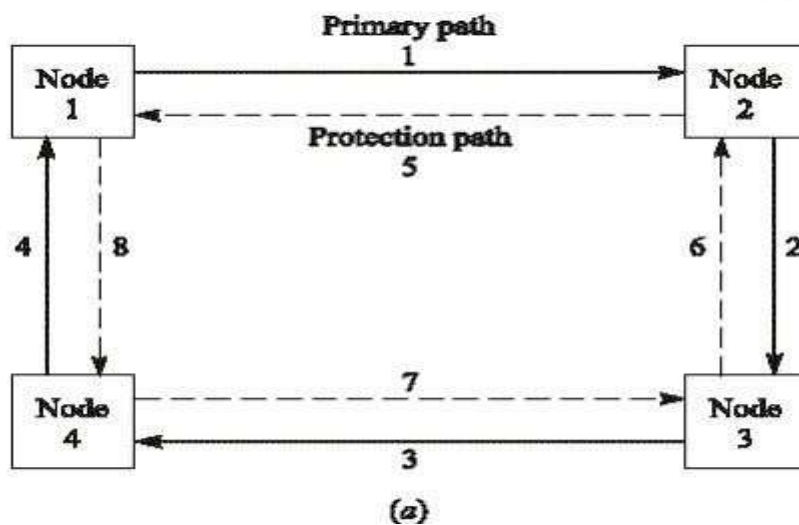


Figure 5.3 Generic 2-fiber UPSR with a counter-rotating protection path

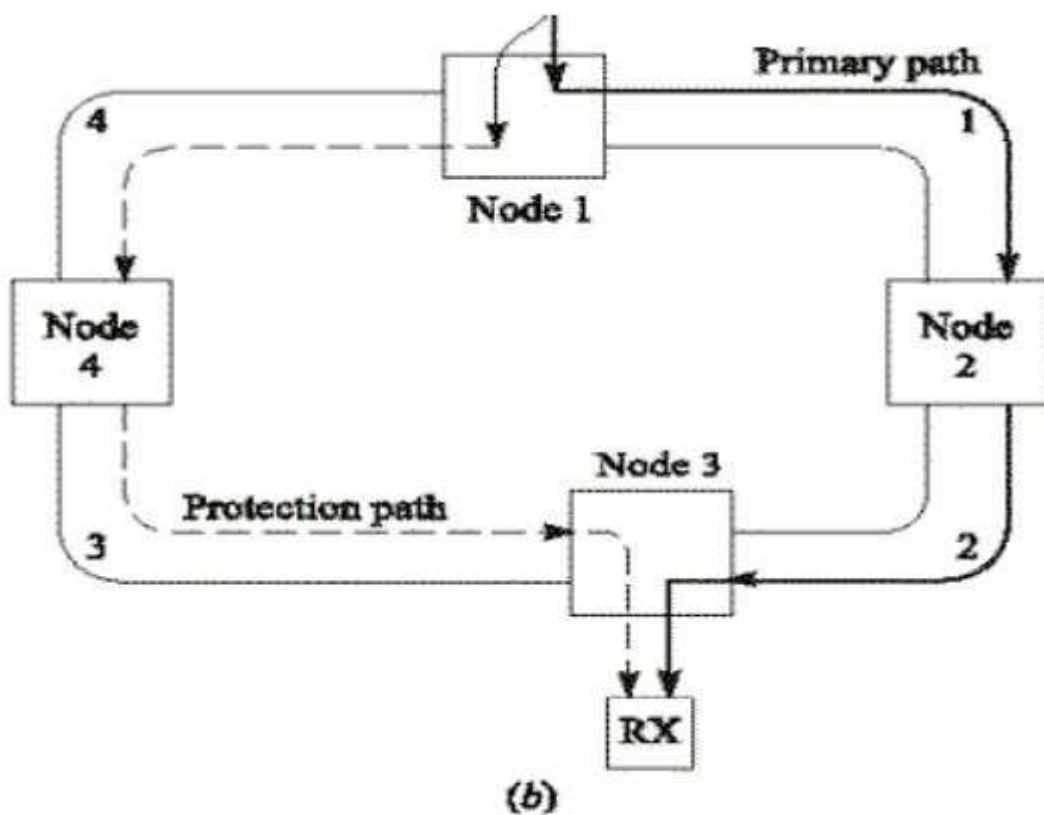


[Source: <http://img.brainkart.com>]

Ex: Total capacity OC-12 may be divided to four OC-3 streams, the OC-3 is called a path here

2-Fiber UPSR Protection:

- ✓ Rx compares the signals received via the primary and protection paths and picks the best one
- ✓ Constant protection and automatic switching

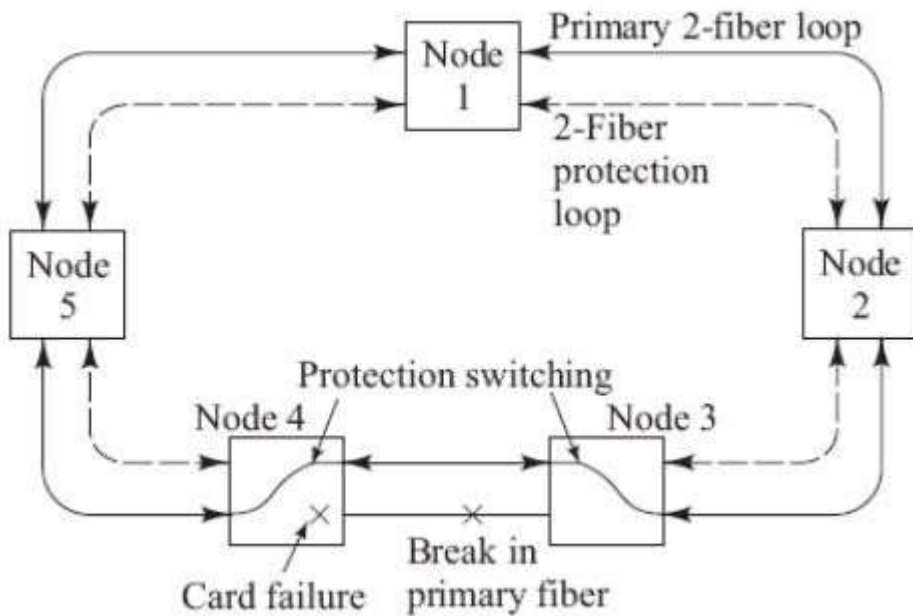


[Source: <http://img.brainkart.com>]

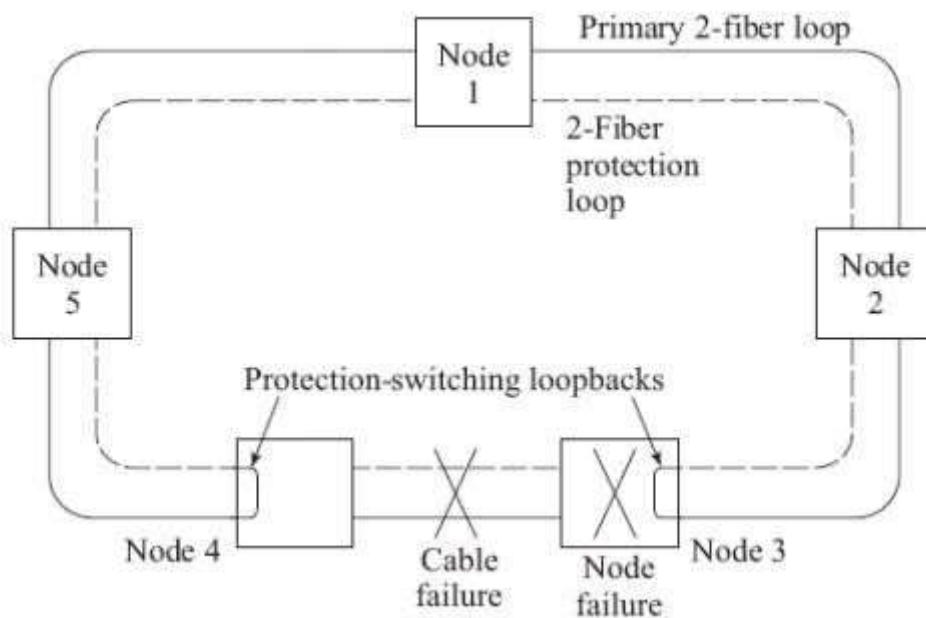
BLSR Recovery from Failure Modes:

- ✓ If a primary-ring device fails in either node 3 or 4, the affected nodes detect a loss-of-signal condition and switch both primary fibers connecting these nodes to the secondary protection pair

- ✓ If an entire node fails or both the primary and protection fibers in a given span are severed, the adjacent nodes switch the primary-path connections to the protection fibers, in order to loop traffic back to the previous node.

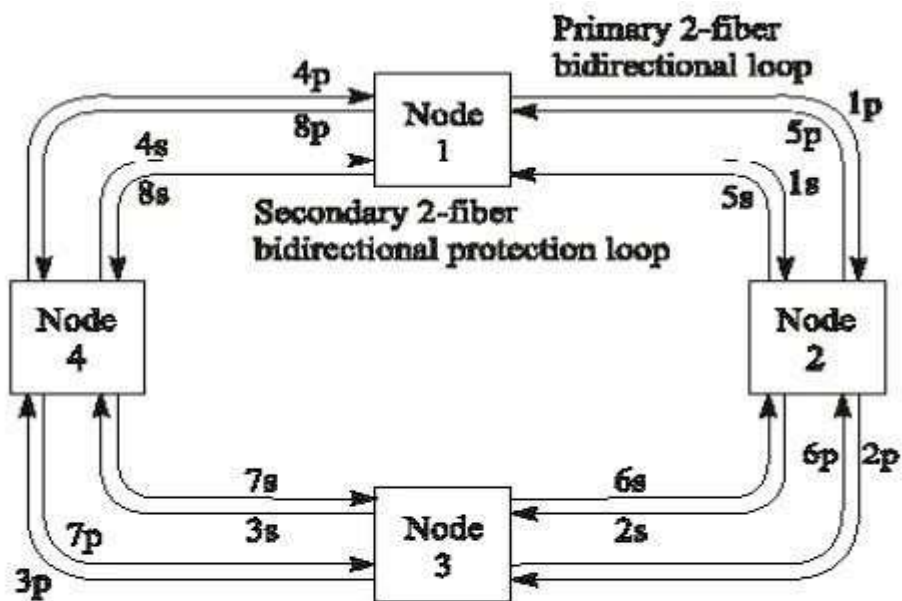


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[Source: <http://img.brainkart.com>]

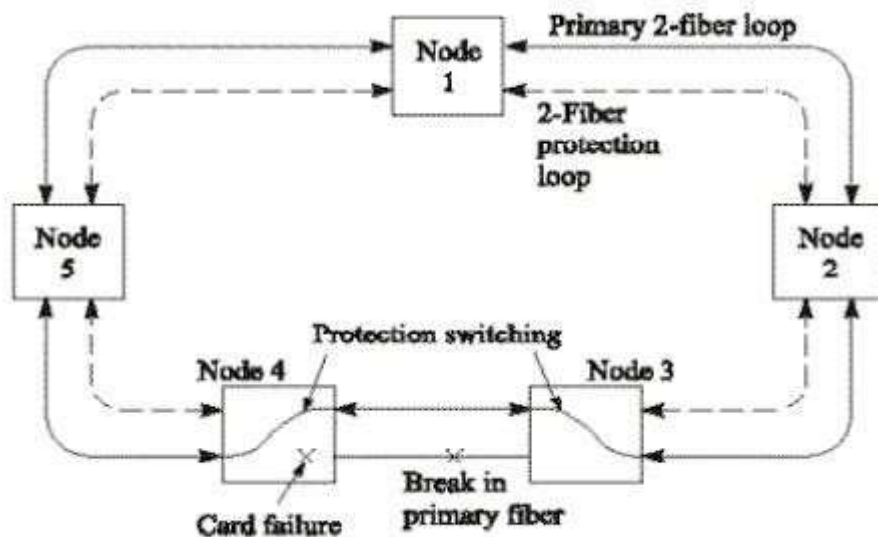
4-Fiber BLSR Basics:



Node 1 → 3; 1p, 2p Node 3 → 1; 3p, 4p

[Source: <http://img.brainkart.com>]

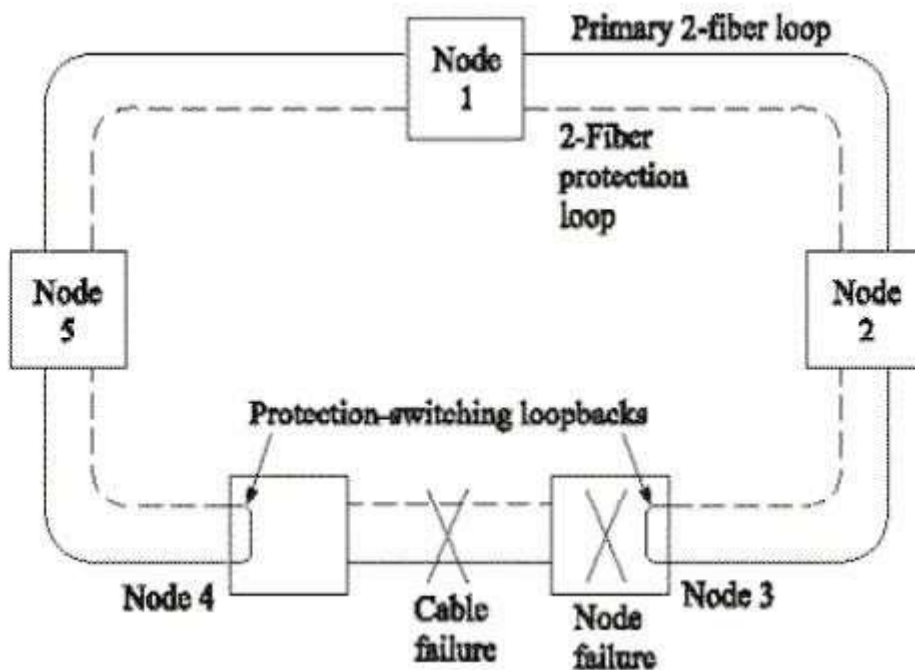
BLSR Fiber-Fault Reconfiguration:



[Source: <http://img.brainkart.com>]

In case of failure, the secondary fibers between only the affected nodes (3 & 4) are used, the other links remain unaffected

BLSR Node-Fault Reconfiguration:



[Source: <http://img.brainkart.com>]

If both primary and secondary are cut, still the connection is not lost, but both the primary and secondary fibers of the entire ring is occupied.

Wavelength Routed Networks

- Two problems arise in broadcast and select networks,
- More wavelengths are needed as the number of nodes in the network grows.
- Without the widespread use of optical booster amplifiers, due to this splitting loss is high.
- Wavelength routed networks overcome these limitations through wavelength reuse, wavelength conversion, and optical switching.
- The physical topology of a wavelength routed network consists of optical wavelength routers interconnected by pairs of point-to-point fiber links in an arbitrary mesh configuration.

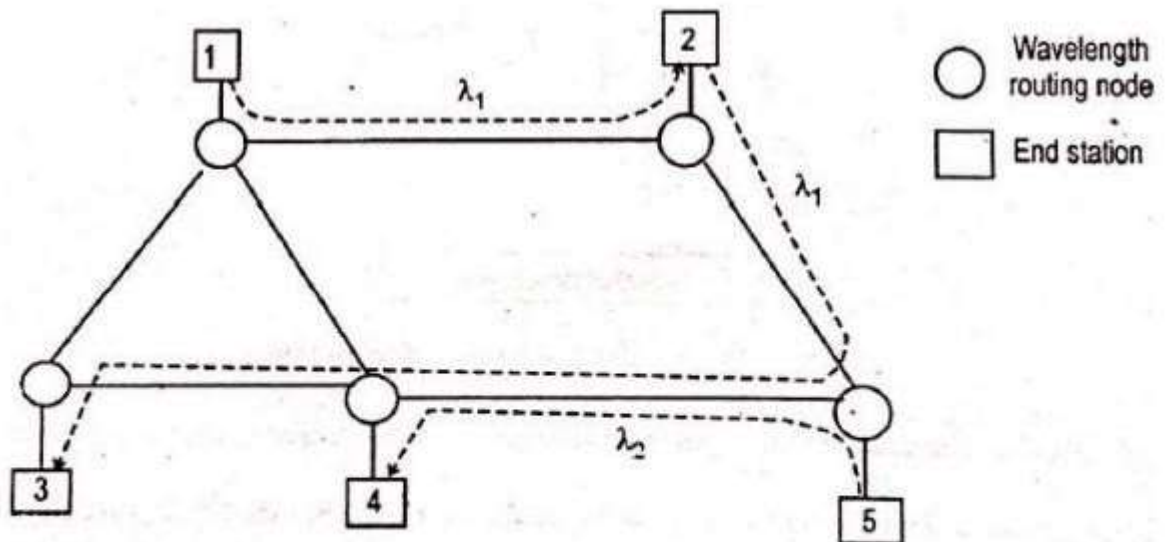


Figure 5.10 Wavelength Reuse on Mesh Network

[Source: <http://img.brainkart.com>]

- Each link can carry a certain number of wavelengths which can be directed independently to different output paths at a node.
- Each node may have logical connections with several other nodes in the network, where each connection uses a particular wavelength.
- The paths taken by any two connections do not overlap, they can use the same wavelength.

1. Optical Cross Connect

- The concept of an optical cross connect architecture is the physical path structure, have a high degree of path modularity, capacity scaling, and flexibility in adding or dropping channels at a user site can be achieved.
- The physical path structure is called as path layer.
- These cross connects (OXC) operate in the optical domain and can route very high capacity WDM data streams over a network of interconnected optical paths.

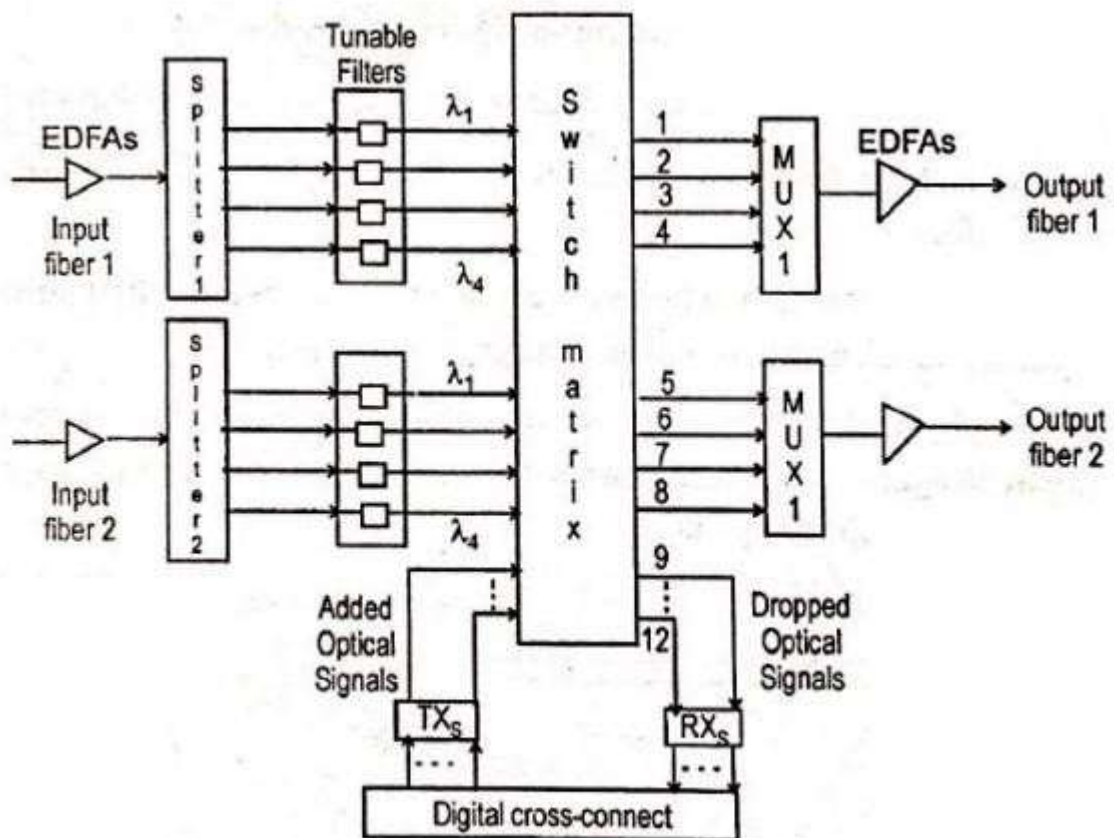


Figure 5.11 Optical Cross Connect Architecture

[Source: <http://img.brainkart.com>]

- OXC architecture uses space switching without wavelength conversion.
- The space switching can be constructed of a cascade of electronically controlled optical directional-coupler elements or semiconductor-optical-amplifier switching gates.
- Each of the input fiber carries a M wavelengths.
- The input, arriving aggregate if signal wavelength is amplified and divided into N streams by a power splitter.
- Tunable filter then select individual wavelengths, which are directed to an optical space switching matrix.
- A waveguide grating demultiplexer could be used to divide the incoming aggregate stream into individual wavelength channels.
- The switch matrix directs the channels either output lines, or to a particular receiver attached to the OXC at outputs ports 9 through 12.
- Signals that are generated locally by a user get connected electrically via the digital cross connect matrix (DXC) to an optical transmitter.
- They enter the switch matrix, which directs them to the appropriate output line.
- The M output lines, each carrying separate wavelength, are fed into a wavelength multiplexer ('mux' and a demultiplexer is 'demux') to form a single aggregate output stream.
- An optical amplifier to boost the signal level for transmission over the trunk fiber.

2. Performance Evaluation of Wavelength Conversion

- These effects are
 - (1) Probability models
 - (2) Deterministic algorithms
- The benefits are greater in a mesh network than in a ring or fully connected network.

The Effect of Wavelength Conversion

- Simple model, circuit switched networks is used.
- The probability that a wavelength is blocked along a path.
- It provides insight into the network performance improvement using wavelength conversion.
- Assume H links (or hops) between two nodes A and B .
- The expected number of busy wavelength on any link is ρF , where ρ is a measure of the fiber utilization along the path and F is the number of a available wavelengths per fiber link.

Broadcast and Select WDM Networks

- All-optical WDM networks have full potential of optical transmission capacity and versatility of communication networks beyond SONET architectures.
- These networks can be classified as
 - (1) Broadcast-and-select techniques
 - (2) Wavelength-routing networks.
- Broadcast-and select techniques employing passive optical stars, buses and wavelength routers are used for local networks can be classified as
 - (1) Single-hop networks
 - (2) Multi-hop networks
- Single hop refers to network where information transmitted in the form of light reaches its destination without being converted to an electrical form at any intermediate point. In a multi hop network, intermediate electro-optical conversion can occurred.

1. Broadcast and Select Signal Hop Network

- Two alternate physical architectures for a WDM-based local network have n sets of transmitters and receivers are attached to either a star coupler or a passive bus.

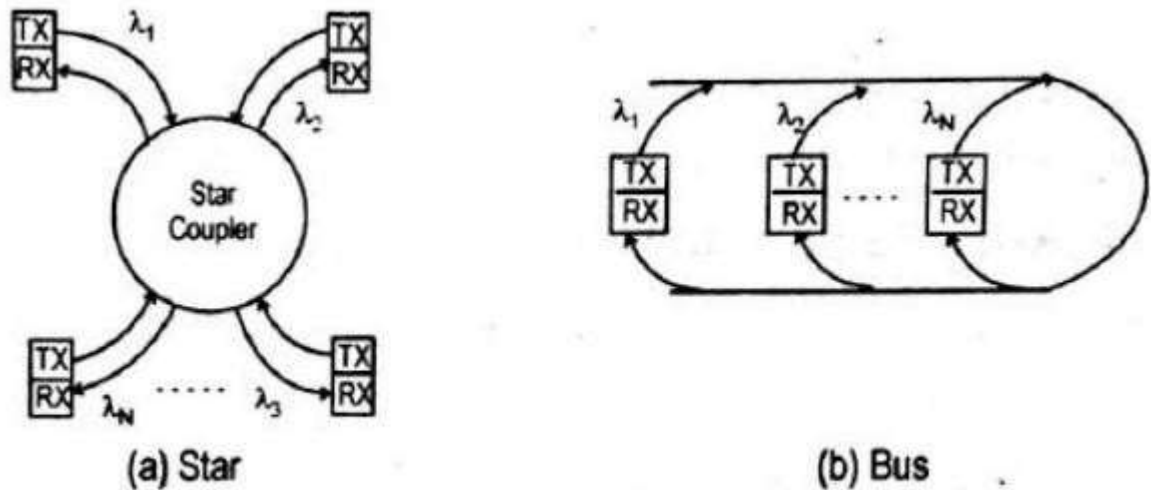


Figure 5.5 Physical architecture of WDM based local network

[Source: <http://img.brainkart.com>]

- Each transmitter sends its information at a fixed wavelength.
- All the transmissions from the various nodes are combined in a passive star. Coupler or coupled onto a bus and sent out to all receivers.
- An interesting point to note is that the WDM setup is protocol transparent.

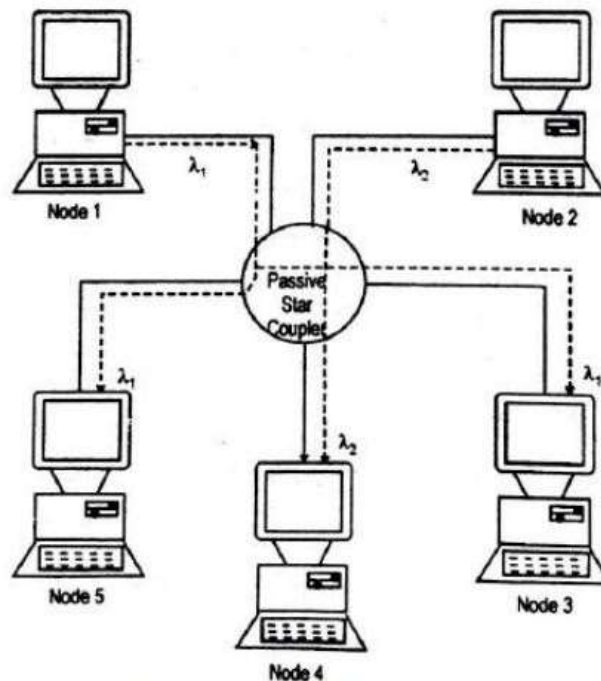


Figure 5.6 Architecture of single hop network

[Source: <http://img.brainkart.com>]

- Protocol transparent means that different sets of communicating nodes can use different information exchange rules (protocols) without affecting the other nodes in the network.
- The architectures of single-hop broadcast-and-select networks are fairly simple, there needs to be careful dynamic coordination between the nodes.
- A transmitter sends its selective filter to that wavelength.
- Two sending stations need to coordinate their transmission so the collisions of information streams at the same wavelength do not occur.

2. Broadcast and Select Multihop Network

- Drawback of single-hop networks is the need for rapidly tunable lasers or receiver optical fibers.
- This drawback can be overcome by the designs of multihop networks.
- Multihop networks do not have direct paths between each node pair.
- Each node has a small number of fixed tuned optical transmitter and receivers.

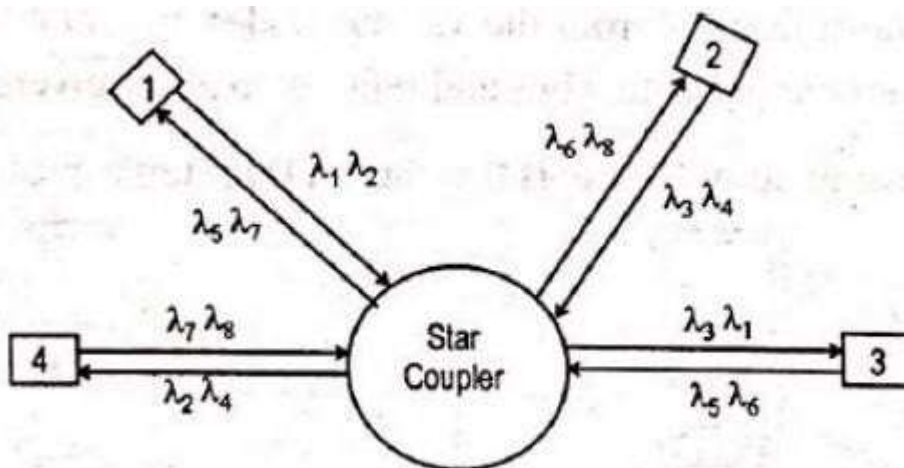


Figure 5.7 Broadcast and select Multihop networks

[Source: <http://img.brainkart.com>]

- An example, a four node broadcast and select multihop network where each node transmits on one set of two fixed wavelengths and receives on another set of two fixed wavelengths.
- Information destined for other nodes will have to be routed through intermediate stations.
- Considering the operation, a simplified transmission scheme in which message are sent as packets with a data field and an address header containing source and destination identifiers (i.e., routing information) with control bits.

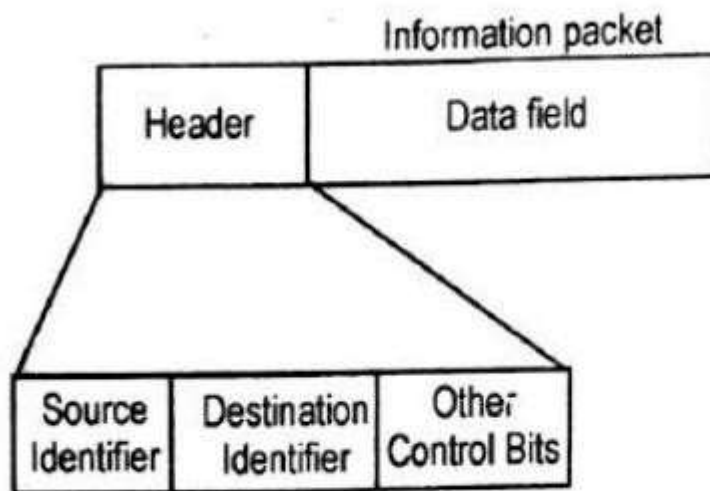


Figure 5.8 Simple representation of fields contained in a data packet

[Source: <http://img.brainkart.com>]

- At intermediate node, the optical signal is converted to an electrical format.
- The address header is decoded to examine the routing information field, which will indicate where the packet should go.
- Routing information is used to send the electronic packets from optical transmitter to the next node in the logical path toward its final destination.
- **Advantage:** There are no destination conflicts or packet collisions in the network.
- For H hops between nodes, there is a network throughput penalty of at least $1/H$.

3. The Shuffle Net Multihop Network

- Various topologies for multihop light wave networks are
 - (1) The shuffle net graph
 - (2) The de Bruijn graph
 - (3) The toroidal Manhattan street network
- A scheme called the perfect shuffle is widely used to form processor interconnect patterns in multiprocessors.
- For optical networks, the logical configuration consists of a cylindrical arrangement of k columns, each having p nodes. Where P is the number of fixed transceiver pairs per node.
- The total number of nodes is then

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$$N = kp^t \quad \dots (5.18)$$

where $k = 1, 2, 3, \dots$

$p = 1, 2, 3, \dots$

- The total number of wavelengths N_λ needed in the network is

$$N_\lambda = pN = kp^{t+1} \quad \dots (5.19)$$

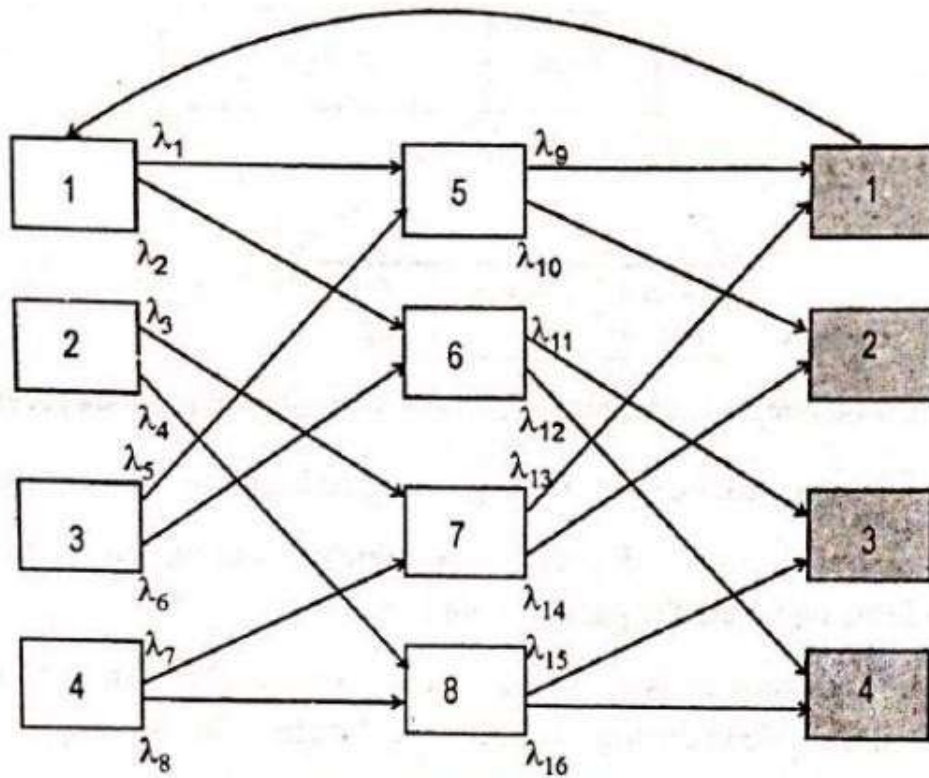


Figure 5.9 Shuffle Net

[Source: <http://img.brainkart.com>]

- a $(p,k)=(2,2)$ shuffle net, where the $(k+1)$ th column represents the completion of a trip around the cylinder back to the first column.
- Performance parameter for the shuffle net is the average number of hops between any randomly chosen nodes.
- Since, all nodes have p output wavelength, p nodes can be reached from any node in one hop, p^2 additional nodes can be reached in two hops, until all the $(pk-1)$ other nodes are visited.
- The maximum number of hops is

$$H_{max} = 2k - 1 \quad \dots (5.20)$$

- Consider figure above, the connections between nodes 1 and 5 and nodes 1 and 7. In first case, the hop number is one.
- In second case three hops are needed with routes 1- 6 – 7 or 1 – 5 – 2-7.?

- The average of hops Bar H of a shuffle net is
 - The average number of hops \bar{H} of a Shuffle Net is

$$\bar{H} = \frac{1}{N-1} \left[\sum_{j=1}^{k-1} j p^j + \sum_{j=0}^{k-1} (k+j) + (p^k - p^j) \right]$$
$$= \frac{kp^k(p-1)(3k-1) - 2k(p^k-1)}{2(p-1)(kp^k-1)} \quad \dots (5.21)$$

- In multiphopping, part of the capacity of a particular link directly connecting two nodes is actually utilized for carrying between them.
- The rest of the link capacity is used to forward messages from other nodes.
- The system has $N_p = kp^{k+1}$ links, the total network capacity C is

$$C = \frac{kp^{k+1}}{\bar{H}} \quad \dots (5.22)$$

- The per-user throughput δ is

$$\delta = \frac{C}{N} = \frac{P}{H} \quad \dots (5.23)$$

- Different (p,k) combination result in different throughputs, to get a better network performance.